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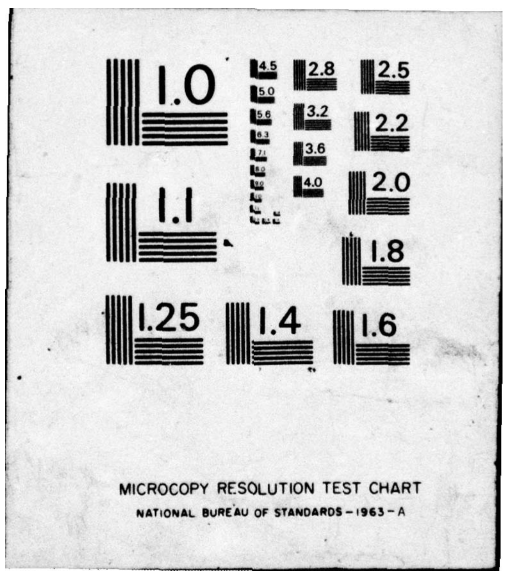
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FUEL AND LUBRICANT COMPATIBILITY STUDIES FOR ARMY HIGH-OUTPUT TWO-CYCLE DIESEL ENGINES

(12)

INTERIM REPORT
AFLRL No. 80

by

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Diesel Engines	Tactical Equipment	

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

A high-output Army two-cycle diesel engine was subjected to proving-ground related laboratory-dynamometer endurance test cycles using four different qualified MIL-L-2104C SAE grade 30 lubricants. Three diesel fuels differing mainly in sulfur level and end point temperature were an important part of the test matrix. Two lubricants (low- and mid-ash level) produced acceptable performance and a third (of high-ash level) was considered borderline acceptable--all during operation with reference

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20. Abstract (cont.)

No. 2 diesel fuel (0.42% wt sulfur). A fourth oil (low-ash level) was judged to be incompatible due to its proneness to severe piston and liner scuffing. The engine was judged incompatible with a high sulfur/high end-point [1.2%S/396°C (744°F) EP] fuel intended to meet MIL-F-16884F (Marine Diesel Fuel) using two different MIL-L-2104C lubricants. This engine was also judged to be incompatible with a special blend of NATO F-54 diesel fuel (0.64% sulfur) during operation with the same two lubricants. Incompatibility using fuel sulfur levels greater than 0.50% was based on the occurrence of catastrophic piston/ring/exhaust valve failure and relatively high deposit and wear levels.

FOREWORD

The work reported herein was conducted at the U.S. Army Fuels and Lubricants Research Laboratory (USAFLRL), located at SwRI, San Antonio, Texas, under Contracts DAAD05-70-C-0250, DAAK02-73-C-0221, and DAAG53-76-C-0003, during the period September 1972 through September 1975. The contract monitor was Mr. C.F. Schwarz, USAMERDC-CCL, through June 1974, and Mr. F.W. Schaekel, USAMERADCOM, Laboratory 2000, from June 1974 through the completion of this work.

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INTRODUCTION

The major portion of the crankcase oil used by Army *combat/tactical* equipment during the 1960's was furnished under two Military Specifications: MIL-L-2104B, Lubricating Oil, Internal Combustion Engine (Heavy Duty)[1]* and MIL-L-45199 (Revisions A and B), Lubricating Oil, Internal Combustion Engine (High Output Diesel)[2]. MIL-L-2104B oils were used for lubrication of units powered by spark-ignition and low-to-medium output compression-ignition engines, while MIL-L-45199 oils were designated for use in equipment with high-output compression-ignition powerplants. In late 1970, these specifications were superseded by Military Specification MIL-L-2104C, Lubricating Oil, Internal Combustion Engine, Tactical Service[3]. The new specification represented a significant departure from the dual-specification approach in that all tactical equipment, irrespective of engine type (spark- or compression-ignition) and output level were to be lubricated with oils supplied under a single specification. Application of the new specification products to the entire *tactical fleet* changed the level of engine oil performance, and it was necessary to establish engine-lubricant compatibility of the MIL-L-2104C oils as had been demonstrated for the superceded specification products.

To meet this determined need, a compatibility program was initiated by the U.S. Army Mobility Equipment Research and Development Command, Laboratory 2000 (formerly Coating and Chemical Laboratory at Aberdeen Proving Ground, Md). The objective of the program was to develop the data necessary for evaluating the compatibility of qualified MIL-L-2104C lubricants with current engines used in Army *combat/tactical* vehicles. Making use of the baseline lubricants performance data enabled the Army to further check engine compatibility using two additional diesel fuels of differing composition. This paper addresses the problems of engine-fuel-lubricant compatibility pertaining to the Army's large inventory of combat/tactical ground-vehicle *two-cycle diesel engines*.

DIESEL FUEL AND THE ARMY TWO-CYCLE DIESEL ENGINE

The U.S. Army combat/tactical ground-vehicle fleet is powered by a mixture of both two-stroke and four-stroke cycle diesel engines. The two-cycle diesels are of *one family*, and the engine manufacturer specifies fuel having maximum permissible sulfur and distillation end-point temperature levels of 0.50% wt and 357°C (675°F) respectively. Accordingly, continuous usage of fuels whose sulfur level and distillation end-point temperature exceed these values could be expected to cause increased wear and deposition problems in the Army's ground-vehicle *two-cycle* diesel engine *family*[4]. Typically, U.S. Army diesel fuels procured *in* and used *in* continental United States (CONUS) are below the maximum sulfur level and distillation end-point temperature specified by the engine manufacturer. Such fuel has normally been procured against U.S. Federal Specification VV-F-800A[5].

*Superscript numbers indicate references at end of paper.

During recent years, military procurement of diesel fuels *outside* continental United States (OCONUS) involved the purchase of fuels which did not meet the requirements of U.S. Federal Specification VV-F-800A. Because of a request by the U.S. Forces Commander-in-Chief in Europe (USCINCEUR) for standardization of diesel fuels available within the NATO pipeline, VV-F-800A was recently modified[6] to include diesel fuels procured for both domestic (CONUS) and OCONUS usage. Essentially, the modification (in VV-F-800B) establishes the permissible sulfur level and 90% distillation temperature for OCONUS DF-2 usage at the latest values covered by the NATO guide specification for F-54 diesel fuel[7,8], and it also raised the maximum permissible end-point distillation temperature for both CONUS and OCONUS usage from 355°C to 371°C (671°F to 700°F). The maximum permissible 90% distillation temperature for fuel procured for CONUS usage was also raised slightly from 330°C to 338°C (626°F to 640°F). The maximum permissible 90% and end-point distillation temperatures specified in VV-F-800B are, however, still *lower* than that permitted in MIL-F-16884F (or MIL-F-16884G), a specification[9,10] against which diesel fuel has been frequently procured for OCONUS usage, particularly in the Southeast Asia and Mediterranean areas.

CURRENT TEST PROGRAM

Previous investigations conducted in the 1960's[11] showed that engine-fuel-lubricant compatibility could be evaluated by accelerated tests conducted in the laboratory and that the background data and experience acquired could be used to prevent the occurrence of serious field problems. It was decided to use the dynamometer techniques developed during the earlier work for the current program. In conjunction with three representative MIL-L-2104C lubricants, two compression-ignition engine configurations (a two-cycle liquid-cooled, and a four-cycle air-cooled) were selected for testing. Initially, two tests were scheduled to be conducted with each oil, and one test with each engine configuration, for a total of six compatibility tests. However, after the program was initiated, it became evident that the scope of work should be expanded to include two additional important areas of concern. These were (1) the effects of mid to high level sulfur/end point diesel fuels and (2) the test-cycle severity effects as related to the specific military vehicle application. Additionally, as the program progressed, it became of significant interest to check the compatibility of an *actual fielded* MIL-L-2104C lubricant in both of the above classes of Army engines, since the original three test oils were qualified products but not available in the government supply system.

Test Engines

Specific two- and four-cycle diesel engines selected for this program were known to be critical of lubricant quality and therefore would provide maximum assurance of lubricant compatibility. The four-cycle, air-cooled diesel engine work, utilizing the AVDS-1790-2A M60 series tank engine, was conducted at Anniston Army Depot, and those results

will be discussed in another paper. The liquid-cooled, two-cycle diesel engine work was conducted at the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL)[12-15], using the 6V53T, whose characteristics are shown in Table 1. Note that this engine is equipped with trunk type pistons. End use for this engine is the M551-Sheridan, Armored Reconnaissance/Airborne Assault Vehicle, Full Tracked, 152mm; a picture of which is shown in Figure 1. The 6V53T engine was selected because it is *typical* of the family of two-cycle diesel engines found in today's

TABLE 1. 6V53T ENGINE CHARACTERISTICS

Engine type	Turbocharged, two-cycle compression ignition, direct injection uniflow scavenging
Weight (dry), kg (lb)	495.33 (1092)
No. of cylinders, arrangement	6, V
Displacement, liters (cu in.)	5.212 (318)
Bore and stroke, cm (in.)	9.84 × 11.43 (3-7/8 × 4-1/2)
Cylinder block material	Aluminum, with cast iron liners
Rated power, kW (Hp)	186.45 (300) at 2800 rpm, at 16°C (60°F) and 760 mm (29.92 in.) Hg
Maximum torque, Nm (lb-ft)	833.82 (615) at 2200 rpm
Compression ratio	17 to 1
Fuel system	Unit injectors (N 70, needle valve), primary and secondary engine filters
Governor	Limiting speed, double weight
Oil sump capacity, liters (gal.)	18.93 (5)
Oil filter	Full-flow single filter
Oil cooling	Integral heat exchanger using 100 percent jacket-coolant flow
Piston description	
Material/design	Cast iron/trunk type
Ring configuration	1–Fire ring (rectangular) 3–Compression rings (rectangular) 2–Oil rings
Piston cooling	From jet in top of connecting rod

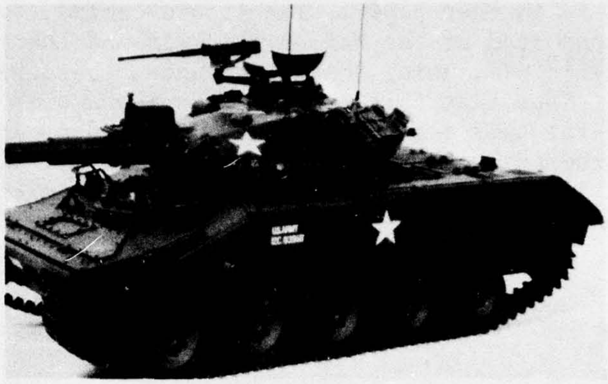


Fig. 1 - M551 Armored reconnaissance/airborne assault vehicle - "Sheridan"

Army, i.e., the 6V53, 3-53, 8V71T, and 12V71T *trunk-piston* equipped engines used throughout the combat vehicle fleet as illustrated in Table 2. In addition, the high-power-to-weight ratio of *this* specially-designed *military* engine, *necessitated by its vehicle's mission, unlike any commercial counterpart,* makes it very critical of oil quality, particularly in the area of piston ring/cylinder liner scuffing tendencies(16-19). Therefore, it was believed that selection and use of this engine in the current program would provide *maximum assurance* of lubricant compatibility. The engine test facility is shown in Figure 2.

Test Oils

The four qualified MIL-L-2104C engine oils selected for this program represent a cross-section of the OE/HDO-30 products qualified under the specification. Comparison of property data with MIL-L-2104C requirements is shown in Table 3. Lubricant codes A and B are low-ash additive products formulated as "Universal Oils" to meet the American Petroleum Institute (API) service classifications CD/SE(20). Code C is a relatively high-ash oil formulated primarily to meet API classification, CD. Lubricant code D is a mid-ash *fielded oil* of CD performance level which was drawn from the government supply system for the purposes of this program.

Test Fuels

The diesel fuels used in this program comprised one reference No. 2 fuel and two special fuels whose blend properties were adjusted to accomplish the program objectives. Table 4 presents a comparison of the reference test fuel and the two special test fuels along with the blend specification requirements for each fuel. The reference No. 2 diesel fuel is a nominal VV-F-800B No. 2 diesel fuel conforming to the requirements established by Federal Test Method Standard 791B, Method 341.4(21); and is a straight-run, mid-range natural sulfur fuel which is manufactured under closely controlled refinery operation to minimize batch-to-batch compositional and physical property deviations.

TABLE 2. ARMY TACTICAL VEHICLES POWERED BY GMC DETROIT DIESEL TWO-CYCLE ENGINES

Designation	Description	Engine Model
M106A1	Mortar, Self-propelled, 107mm	6V53
M107	Gun, Self-propelled, 175mm	8V71T
M108	Howitzer, Self-propelled, 105mm	8V71T
M109	Howitzer, Medium, 155mm	8V71T
M110	Howitzer, Self-propelled	8V71T
M113A1	Carrier, Personnel	6V53
M125A1	Mortar, Self-propelled, Full-tracked	6V53
M132A1	Flame Thrower, Self-propelled	6V53
M548	Carrier, Cargo, Tracked, 3442 kg (6-ton)	6V53
M551	Armored Reconnaissance/Airborne Assault Vehicle (Sheridan)	6V53T
M561	Gamma Goat	3-53
M577A1	Carrier, Command Post, Light Tracked	6V53
M578	Recovery Vehicle	8V71T
HET70	Heavy Equipment Transporter	12V71T
XM 667	Carrier, GM, Equipment, SP	a
XM 727	Carrier, GM, Equipment, SP	a
XM 730	Carrier, GM, Equipment, SP	a
XM 741	Chassis, Gun, AA Artillery, 20mm, SP	a
XM 806E1	Recovery Vehicle, FT Armored	a
–	Truck, Dump, 18 140 kg (20-ton), Diesel Electric Driven	6V71

[a]Vehicles are powered by either 6V53, 6V53T, or 8V71T (TB-750-652).

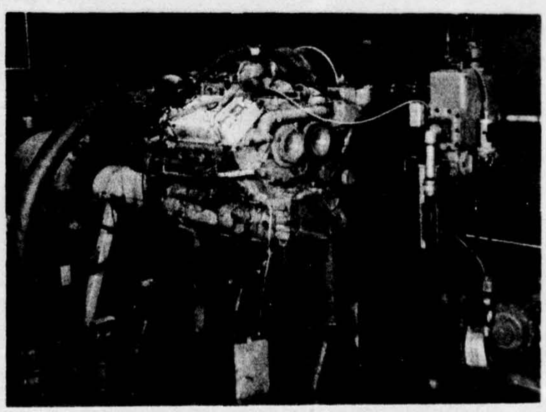


Fig. 2 - Diesel engine model 6V53T test facility

TABLE 3. COMPARISON OF TEST LUBRICANT PROPERTY DATA WITH MIL-L-2104C REQUIREMENTS

Property	ASTM Method No.	Lubricant Code A	B	C	D	MIL-L-2104C Requirements
Viscosity, cSt						
at 99°C (210°F)	D445	12.61	12.24	12.93	12.74	9.6-12.9
at 38°C (100°F)	D445	121.6	119.4	126.7	132.6	Report
Viscosity index	D2270	94	92	101	95	75 (min)
Flash point, °C (°F)	D92	241 (465)	249 (480)	238 (460)	229 (445)	218 (425) (min)
Pour point, °C (°F)	D97	−20.6 (−5)	−20.6 (−5)	−20.6 (−5)	−17.8 (0)	−17.8 (0) max
Gravity, °API	D287	27.4	27.4	27.3	25.7	Report
Carbon residue, %	D524	1.19	0.93	1.69	1.46	Report
Sulfated ash, %	D874	0.93	0.85	1.75	1.43	Report
Total acid no.	D664	3.6	1.9	3.0	1.6	Report
Total base no.	D2896	5.4	5.6	12.5	11.2	Report
Insolubles, %	D893					
Pentane (A, w/o coag.)		0.03	0.04	0.04	ND	NR
Benzene (A, w/o coag.)		0.02	0.03	0.04	ND	NR
Pentane (B, with coag.)		0.05	0.03	0.04	ND	NR
Benzene (B, with coag.)		0.04	0.02	0.04	ND	NR
Additives, % wt						
Zinc		0.093	0.069	0.093	0.050	Report
Calcium		0.24	0.13	0.44	0.39	Report
Barium		Nil	0.16	Nil	0.03	Report

ND–Not determined, but assumed to be nil.
NR–Not required.

TABLE 4. ANALYSIS OF TEST FUELS

Property	ASTM Method No.	Reference No. 2 DF		MIL-F-16884F (DFM)		NATO F-54	
		Test Fuel[a]	Specification[b]	Test Fuel-HSF[c]	Specification	Test Fuel[d]	Specification[e]
API gravity	D287	33.2	Record	34.1	Record	31.1	33-41.0
Viscosity, cSt, 38°C (100°F)	D445	3.20	1.6-4.5	3.66	2.1-6.0	3.40	1.8-9.5[f]
Flash point, °C (°F)	D93	85 (185)	37.8 (100) min	88 (190)	60 (140) min	96 (205)	56 (133) min
Cloud point, °C (°F)	D2500	−5.0 (+23)	Record	−1.1 (+30)	−12.2 (+10) max	1.1 (+34)	−12.8 (+9) max
Pour point, °C (°F)	D97	−7.8 (+18)	−6.7 (+20) max	−12.2 (+10)	−17.8 (0) max	−9.4 (+15)	−17.8 (0) max
Water and sediment	D1796	0.0	0.5 max	0	0.01 max	ND	0.10 max
Carbon residue, %	D524	0.10	0.20 max	0.14	0.20 max	0.16	0.20 max
Sulfur, %	D129	0.415	0.35 min	1.20	1.00 max	0.64	0.70 max
Acid no.	D664	0.108	Record	0.18	0.50 max	0.17	0.10
Aniline point, °C (°F)	D611	63 (145)	Record	66 (150)	Record	61 (142)	NR
Copper corr.	D130	1A	No. 2 max	1A	1 max	1A	1 max
Distillation, °C (°F)	D86						
IBP		210 (410)	Record	204 (399)	NR	227 (440)	NR
10 %		242 (468)	Record	231 (447)	NR	248 (478)	NR
50 %		271 (519)	260 (500) min	278 (533)	Record	276 (529)	NR
90 %		317 (603)	316-338 (600-640)	359 (679)	357 (675) max	323 (613)	357 (675) max
EP		365 (689)	343-366 (650-690)	396 (744)	385 (725) max	363 (685)	371 (700) max
Cetane no.	D613	47[g]	40-45	50.5	47 min	47	45 min
HHV, J/kg in 100 thousands (Btu/lb)	D240	45.47[h] (19,500)	Record	44.10 (18,960)	NR	45.12[h] (19,400)	NR
Acc. stability, total insol., mg/100 ml	D2274	2.1	NR	1.50	2.5 max	7.4	NR
Ash, %	D482	0.006	0.01 max	ND	NR	0.01	0.02 max

[a]This is fuel used in Tests Nos. 1-5 in Table 5; Tests Nos. 8-10 used this fuel comingled with two later batches.
[b]Section 4.1, Method 341.4, FTM Std. 791B (Reference No. 21).
[c]This is fuel used in Tests Nos. 6 and 7 in Table 5.
[d]This is fuel used in Tests Nos. 11, 12, and 13 in Table 5.
[e]Limits are from Annex C, NATO STANAG 2845.
[f]Viscosity range at 20°C (68°F).
[g]Calculated Cetane Index, ASTM Method D976.
[h]Calculated higher value from gravity, viscosity, and distillation properties.

ND–Not determined.
NR–Not required.

The second fuel in Table 4 was blended to generally conform to the specification limits of Military Specification MIL-F-16884F, diesel fuel, marine (DFM). The upper limit of sulfur (1%) and distillation end point [385°C (EP 725°F)] were selected to assure that the fuel represented the most severe blend that might be found in the logistics system. As noted in the table, the sulfur level of the procured fuel, referred to simply as the high sulfur fuel (HSF), was *higher* than the specification limit by 0.2% weight, along with the distillation end point that was *above* the desired limit by 10.6°C (19°F). Since this fuel procurement was not obtained from a normal refinery run, these deviations from the specification were permitted.

The third test fuel was blended to generally conform to the limits of the NATO F-54 Guide Specification. The blend was targeted towards the upper limit of sulfur (0.70%) and distillation end-point [363°C (EP 685°F)] to assure that the fuel represented the most severe blend that might be found in the logistics system. The cloud point and pour point of the F-54 test fuel in Table 4 exceed the specifications values by 13.9°C (25°F) and 8.3°C (15°F) respectively. The API gravity and acid number values are also slightly outside the specification limits. Since this fuel procurement was not obtained from a normal refinery run, these deviations from the specification were permitted. Additional non-routine analyses were conducted on the F-54 test fuel and its components and these results are presented and discussed in a later section of the paper.

Endurance Test Methods

Two laboratory engine test procedures previously developed by the Army in cooperation with the Coordinating Research Council (CRC)[11] were used in the current program. Each test involves cyclic endurance testing of vehicle engines: one, a 210-hr cycle designed to correlate with 32,180 km (20,000 miles) field service of tactical wheeled vehicles, and the other, a 240-hr cycle designed to correlate with 6,436 km (4,000 miles) operation of tracked combat vehicles. In each of these methods engine-fuel-lubricant system compatibility is judged on: (1) the ability of the test engine to maintain performance throughout the cycle; (2) wear developed in engine components; (3) accumulation of fuel and lubricant related engine deposits; and (4) the physical and chemical condition of the lubricant as monitored throughout the test.

Even though the 6V53T powered M551 is a full-track-laying vehicle, it was decided that the initial tests would use the 210-hr wheeled-vehicle test cycle because of prior experience[22,23] using this test cycle with Army two-cycle diesel engines. After the program was underway it became evident that performance data should also be obtained using the 240-hr tracked-vehicle test cycle. The test engine is shown in Figure 2; the salient features of these test methods are shown in Appendix I, and the details are provided in Reference 14.

DISCUSSION

A total of thirteen engine-fuel-lubricant compatibility tests were conducted in the current series. The list of tests is summarized in Table 5 where it can be noted that: four tests completed the targeted endurance hours and one test missed the target by only one-half hour due to exhaust valve seat breakage, *all* using the Reference No. 2 diesel fuel (0.42% *sulfur*); two tests using the *high-sulfur* fuel (HSF, i.e., 1.2% *sulfur*) missed their target by approximately 15 hours each; three tests using the NATO F-54 type fuel (0.64% *sulfur*) failed to achieve their targeted endurance hours; and one of the *low ash* oils failed in three attempts to achieve the targeted performance using the Reference No. 2 diesel fuel due to severe piston/cylinder liner scuffing and scoring (one test was aborted due to glycol coolant leaking into the oil). The following discussion pertains to lubricant, fuel, and test cycle effects and the significant performance parameters are summarized in Tables 6 through 11.

Lubricant Effects

Reference No. 2 Diesel Fuel

Comparing the four MIL-L-2104C lubricants in the 210-Hr wheeled-vehicle test cycle operating with the reference no. 2 diesel fuel (0.42% S) in Table 6 shows that these oils produce widely differing results. For example, analysis of the data for the low-ash oil Code A shows that the engine was in excellent condition at disassembly. This is nearly idealized by the fact that the power and fuel economy increased as shown in Figures 3 and 4, such that the observed power after the 210-hr endurance run was 2 percent higher than the observed pre-test power measurements. The deposit, wear, and used lubricant data show that this lubricant performed well in *all* areas. Condition of typical piston, liner and piston rings is shown in Figures 5 and 6. Similarly, it is evident from the data that the mid-ash Code D *fielded oil* is the overall next best performing lubricant. Analysis of the wear, deposit, and used-lubricant data shows that this oil performed well in all areas despite two cold-pinched fire rings. Typical test parts for this oil are shown in Figures 7 and 8. It is noted that Code D lubricant approaches Code A lubricant in deposit control, and is nearly equal to the high-ash lubricant (Code C) in wear protection. Used oil analyses showed that the Code D lubricant experienced the highest level of degradation (i.e., viscosity, carbon residue, and insolubles increases) and had an iron content a little more than halfway between the low-ash and high-ash oils. Finally, the significant increase in oil ring gap using Code D suggests that a large portion of the used oil iron content came from the oil rings rather than from cylinder liner wear. Overall, it is reassuring to learn that this *fielded oil* produced acceptable performance in one of the most critical Army two-cycle diesel engines.

Concerning the overall performance of the high-ash Code C lubricant, it is noted that this oil produced about the same deposit level in

TABLE 5. 6V53T COMPATIBILITY TEST SUMMARY

Test No.	Engine-Test No.	Oil Code	Test Fuel	Test Hours	Reason For Stopping Test
1	6D5084-3A	B-Low Ash	Ref No. 2	48	Severe scoring in cylinder 3L
2	6D36804-14	A-Low Ash	Ref No. 2	210	Completed test
3	6D5084-4	C-Hi Ash	Ref No. 2	209.5	OK-(Exhaust valve seat breakage in cylinder 2R)
4	6D17104-3	B-Low Ash	Ref No. 2	145	Glycol in oil
5	6D5084-5	B-Low Ash	Ref No. 2	121	Severe scoring in cylinder 2L
6	6D5084-6	C-Hi Ash	HSF	194	Lost power, burned exhaust valve in cylinder 2L
7	6D5204-1	A-Low Ash	HSF	196	High crankcase pressure
8[a]	6D8019-1	A-Low Ash	Ref No. 2	240	Completed test
9[a]	6D5204-2	C-Hi Ash	Ref No. 2	240	Completed test
10	6D8019-2	D-Mid Ash	Ref No. 2	210	Completed test
11	6D8019-3	A-Low Ash	F-54	191	Exhaust valve and fire ring breakage at 105 and 191 hr
12	6D8019-4	C-Hi Ash	F-54	28	Severe scoring in cylinders 2R and 1L
13	6D5204-5	C-Hi Ash	F-54	131	Exhaust valve and seat failure in 3L

[a]Test ran on 240-hr tracked-vehicle cycle; all other tests ran on 210-hr wheeled vehicle cycle.

TABLE 6. LUBRICANT EFFECTS USING REF. NO. 2 FUEL (0.42% SULFUR)

	Oil Code			
	A	B[a]	C	D
Piston ring freedom				
No. hot stuck	0	1	1	0
No. cold stuck/pinched	0	4	0	2
Piston skirt demerits (avg)	3.9	3.3	4.4	3.1
Piston ring groove No. 2, avg % carbon fill	70	57	72	60
Piston weighted total demerits (WTD)	899	862	1183	1057
Cylinder line scuffing, % Area				
Thrust side (avg)	5	18	15	6
Anti-thrust side (avg)	2	3	12	11
Piston ring gap change in thousandths of centimeters (thousandths of inches)				
Fire ring (avg)	5 (2)	10 (4)	13 (5)	13 (5)
Oil rings (avg)	18 (7)	23 (9)	38 (15)	79 (31)
Cylinder liner wear at top in ten thousandths of centimeters (ten thousandths of inches)				
Transverse (avg)	20 (8)	33 (13)	64 (25)	48 (19)
Longitudinal (avg)	10 (4)	10 (4)	15 (6)	30 (12)
Used oil final drain				
% Vis change at 37.8°C (100°F)	8.5	8.5	20.4	30.0
% Vis change at 99°C (210°F)	0.7	0.6	1.5	2.1
Sulfated ash, Δ	0.15	0.08	0.52	0.27
Carbon residue, Δ	0.47	0.25	0.87	1.25
Pentane insol (w/coag.), Δ	0.31	0.07	0.76	1.15
Benzene insol (w/coag.), Δ	0.33	0.06	0.53	0.95
Iron, ppm	54	91	151	116
Lead, ppm	10	6	24	15
Avg oil consumption, kg/hr (lb/hr)	0.30 (0.66)	0.27 (0.60)	0.22 (0.49)	0.20 (0.45)
Operating data (avg)				
Observed power, kW (BHp)	182.7 (294)	182.1 (293)	184.6 (297)	182.7 (294)
Fuel flow, kg/min (lb/min)	0.939 (2.07)	0.943 (2.08)	0.939 (2.07)	0.943 (2.08)
Jacket-out, °C (°F)	83 (181)	83 (180)	83 (181)	83 (182)
Oil sump, °C (°F)	114 (238)	113 (236)	112 (234)	114 (237)
Blowby flow, m^3/hr (cfh/hr)	22.37 (790)	27.19 (960)	28.89 (1020)	20.28 (716)
Endurance hours completed (210-hr target)	210	48, 121	209.5	210

[a]Average of two tests (nos. 1 and 5) except ring sticking is total number observed.

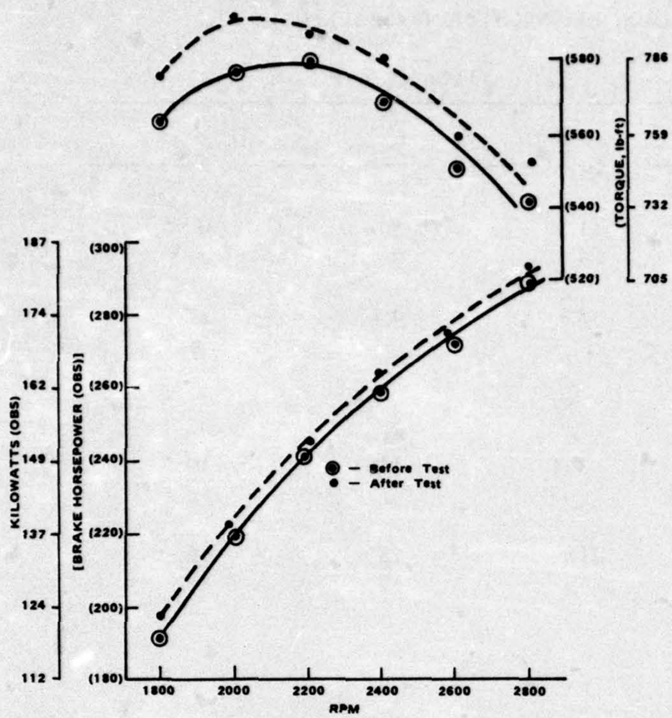


Fig. 3 - Full load performance, test no. 2, 210 hours; oil code A; ref. no. 2 DF

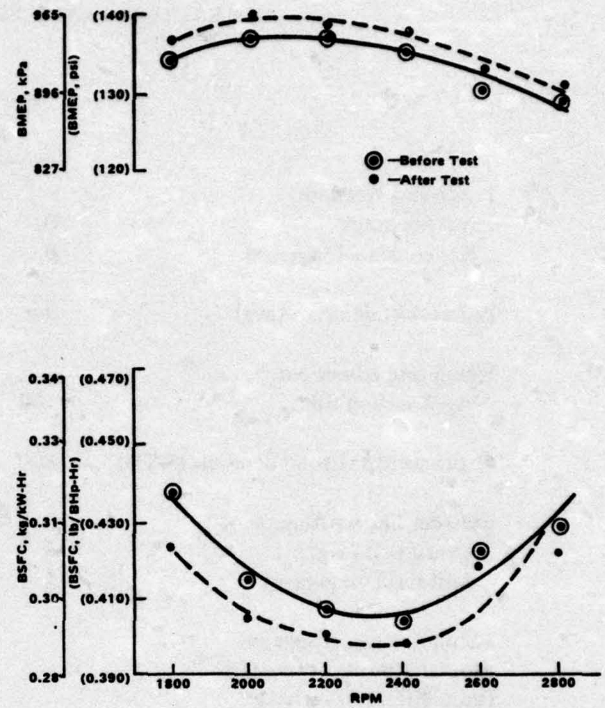
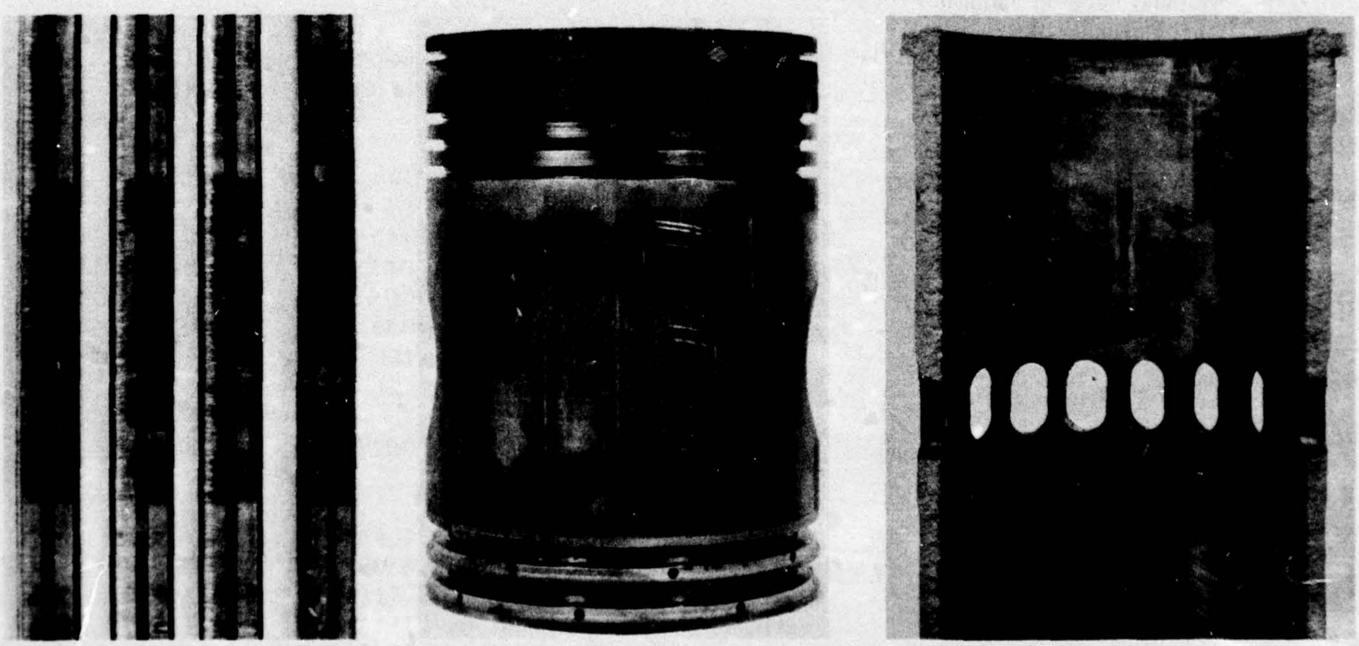


Fig. 4 - Full load performance, test no. 2, 210 hours; oil code A; ref. no. 2 DF



4 3 2 1(F/R)

Fig. 5 - Condition of piston, rings and liner: test no. 2, 1R-thrust, oil code A, ref. no. 2 DF, 210 hrs.

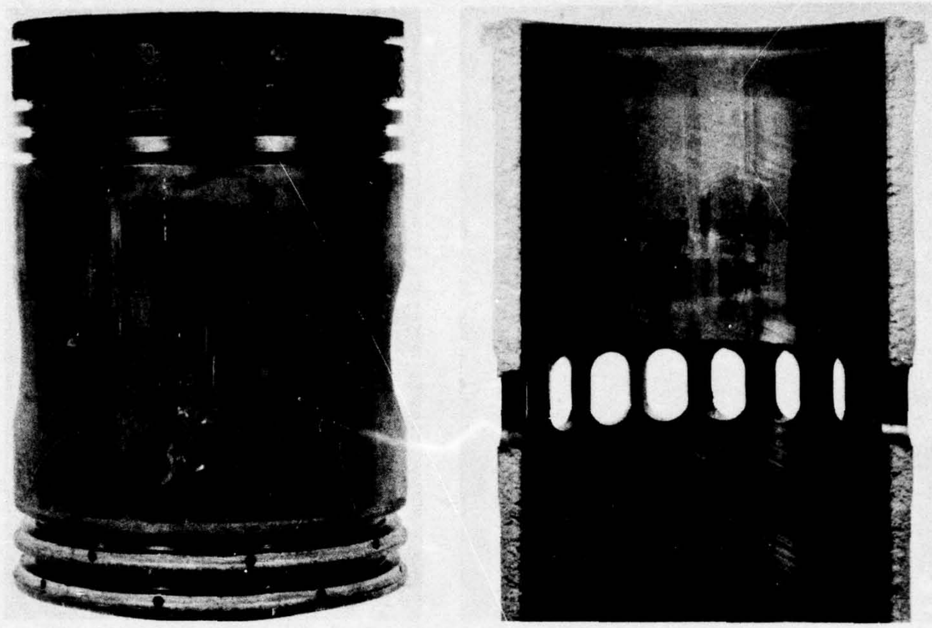


Fig. 6 - Condition of piston and liner: test no. 2, 1R-anti-thrust, oil code A, ref. no. 2 DF, 210 hrs.

the no. 2 compression ring groove compared with the low-ash Code A lubricant (i.e., 72 vs 70% carbon filling) when rated in accordance with the conventional CRC diesel engine method[24]. However, when the approach used in a more recent proposed CRC diesel engine rating method[25] is applied, the pistons run on the Code C lubricant are 32 percent dirtier than those run on the Code A lubricant [(i.e., Weighted Total Demerit (WTD) 1183 *vs* 899, in Table 6]. The reason for the large difference in WTD is that the WTD number, in which 0 = clean, includes the deposits from each of the four ring grooves and four ring lands. The deposits for ring groove nos. 1 and 3 were not included in Table 6, however, Code C lubricant had significantly higher deposits than did Code B lubricant in those two ring grooves (i.e., Code C = 21 and 19% *vs* Code A = 7 and 4% respectively for groove nos. 1 and 3). It is also noted that Code C lubricant produced more cylinder liner scuffing and greater cylinder liner wear and piston ring gap increase than the low ash Code A lubricant. Whether or not the higher initial ash level of Code C lubricant (i.e., 1.75 percent vs 0.93 percent) is the cause of the greater wear or exhaust valve-seat breakage is not known for certain; however, the higher levels of used-oil sulfated ash and elemental iron are further evidence of the higher wear rate using Code C lubricant. Photographs of typical piston, liner and rings are shown in Figures 9 and 10. The overall performance of this lubricant is considered borderline acceptable for Army two-cycle diesel engines because deposit, wear, exhaust valve burning tendencies, and used-oil data suggest there could be wear problems if the test duration were extended beyond 210 hr.

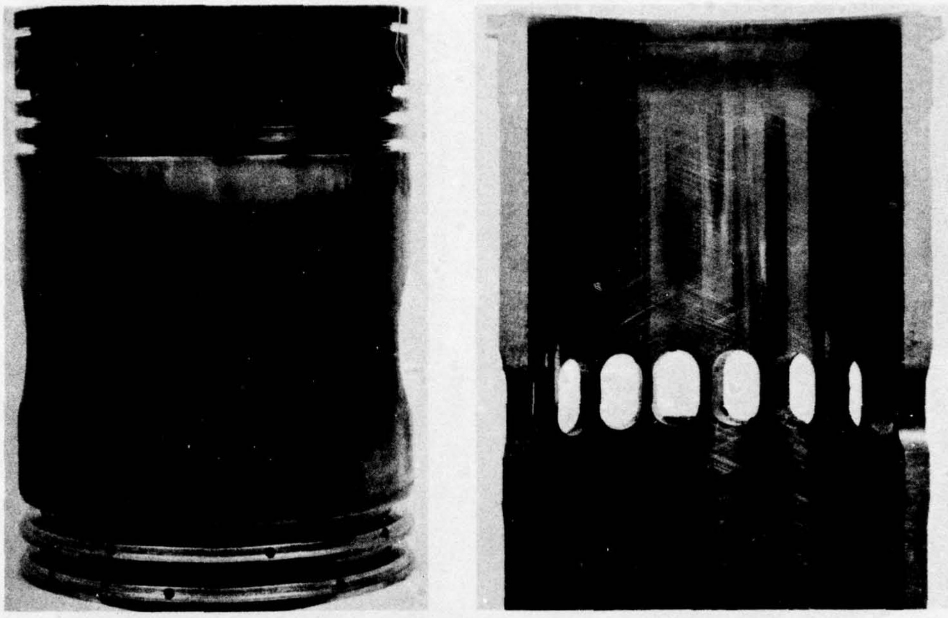
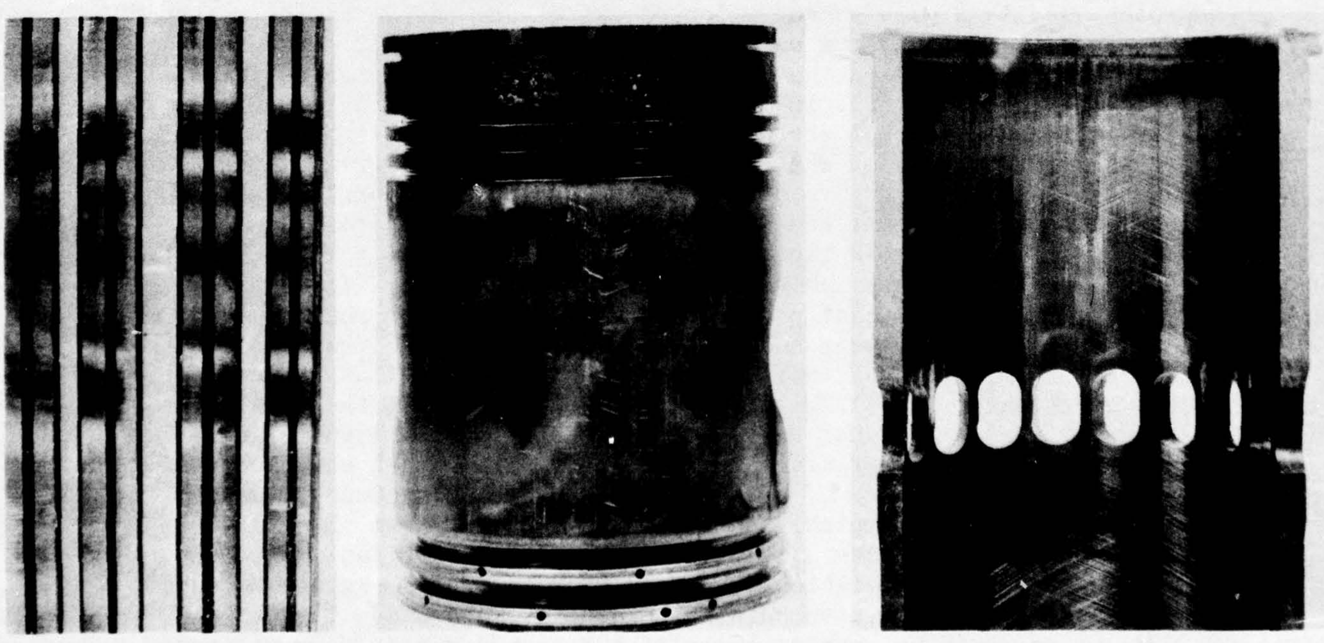


Fig. 7 - Condition of piston and liner: test no. 10, 2R-thrust, oil code D, ref. no. 2 DF, 210 hrs.



4 3 2 1(F/R)

Fig. 8 - Condition of piston, rings and liner: test no. 10, 2R-anti-thrust, oil code D, ref. no. 2 DF, 210 hrs.

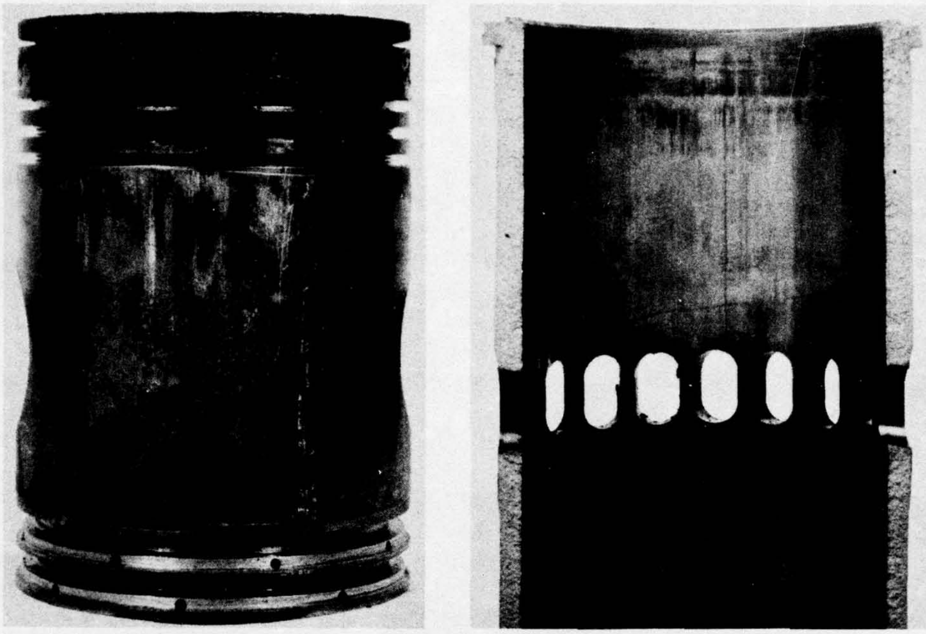
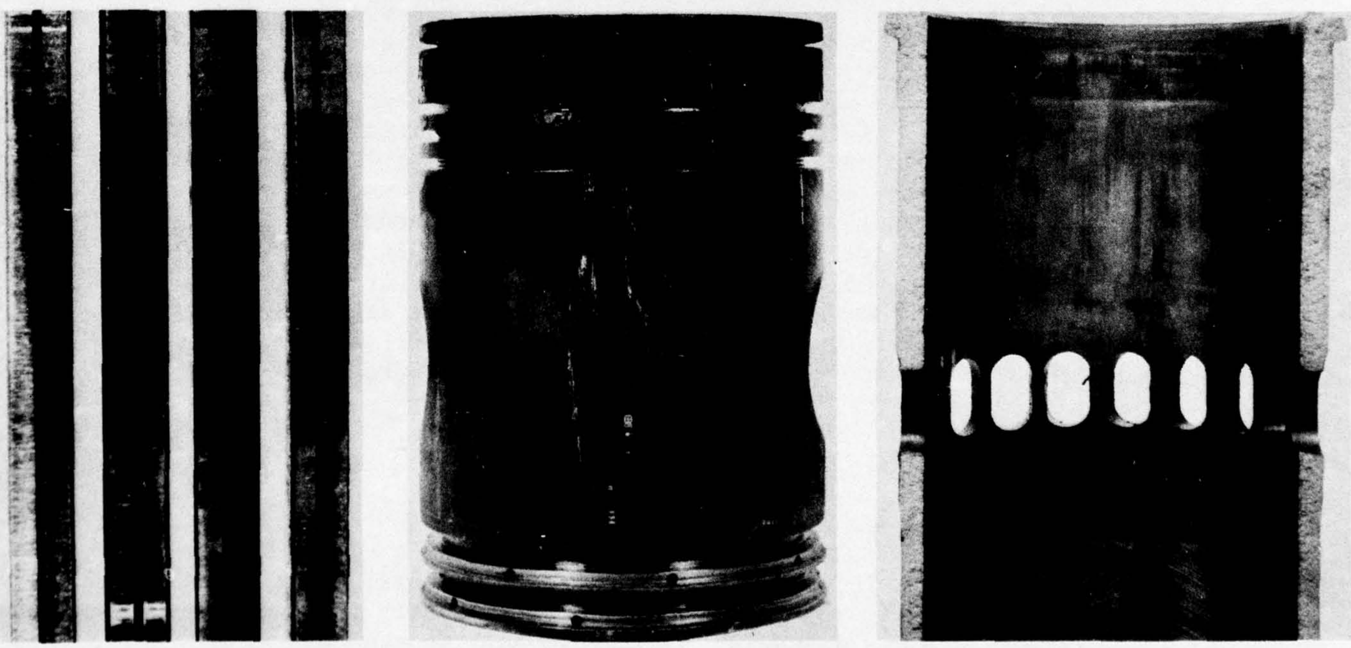


Fig. 9 - Condition of piston and liner: test no. 3, 3R-thrust, oil code C, ref. no. 2 DF, 209.5 hrs.



4 3 2 1(F/R)

Fig. 10 - Condition of piston, rings and liner: test no. 3, 3R-anti-thrust, oil code C, ref. no. 2 DF, 209.5 hrs.

The results discussed thus far strongly suggest that lubricant ash level per se is extremely important for Army two-cycle diesel engine performance. Low-ash level and proper additive content are requirements for *commercial* two-cycle diesel engine applications that have been well documented in the specification cited in Reference 4. However, the *low-ash* Code B lubricant meets the engine manufacturer's *paper requirements*, but the Army's experience with this *low-ash* lubricant shows it is incompatible with *Army procured* two-cycle diesel engines. It is seen in Table 5 that three evaluations, each targeted for 210 hr, were conducted using the Code B lubricant. Each of these tests operated in a normal manner until severe piston-to-liner scoring occurred in one cylinder assembly each in Test Nos. 1 and 5; Test No. 4 was terminated at 145 hr due to glycol coolant leakage into the engine oil system. The engine was not rated for deposits, part condition, and measured wear in the test with the coolant leak because of the nature of the early termination.

Considering the fact that two tests terminated due to piston/liner scoring in only one cylinder (i.e., No. 1 @ 48 hr, Figure 11; and No. 5 @ 121 hr, Figure 12) the signs of lubricant distress were also observed in other sections of the engine. The summarized results in Table 6 for Code B lubricant include the *average values* for the two tests except where the total number of stuck rings is reported. In Test No. 1 there were three cold stuck/pinched fire rings and in Test No. 5 there was one hot stuck and one cold stuck fire ring. The average piston ring zone deposit data do not indicate that the ring sticking or piston/liner scoring problems were deposit oriented. Instead, the deposit levels are comparable with the other low-ash lubricant (Code A). It should be noted, the shorter test lengths undoubtedly caused lower than normal deposit levels for this lubricant. Analysis of the average wear data tends to confirm this lubricant's abnormal wear tendencies. For example, the average cylinder liner thrust side scuffing was 23 percent in Test No. 1 (48 hr), while the average cylinder liner transverse wear was .0046 cm (0.0018 inch) in Test No. 5 (121 hr). These levels of wear are only slightly less than the 209.5 hr test using high-ash lubricant Code C. These data indicate that the Code B lubricant is incompatible with the Army two-cycle diesel engine family due to its proneness to severe piston and liner scuffing, examples of which are shown in Figures 11 and 12, and are similar to those observed and reported earlier using this engine[16-19]. While the cause of the scuffing was not determined, its evidence was confirmed in two tests using the same serial-numbered engine in which Code C lubricant was successfully evaluated (see Table 5).

High-Sulfur Fuel (HSF)

Lubricant Codes A and C were used to determine acceptability of the high-sulfur/ high end-point fuel (Table 5, Test Nos. 6 and 7). Note in Table 7 where the performance of the two oils are compared, that of *most importance*, neither oil protected the engine sufficiently to complete the targeted 210-hr endurance test. In each case, the used-oil iron content is considered exceedingly high suggesting excessive cylinder

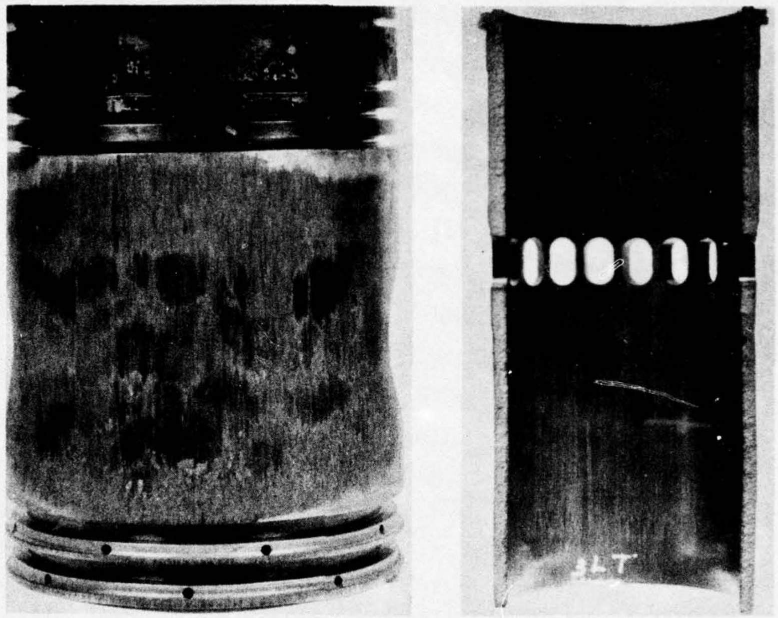


Fig. 11 - Severe piston and liner scoring, test no. 1, cylinder 3L-thrust side, lubricant code B, ref. no. 2 DF, 48 hours.

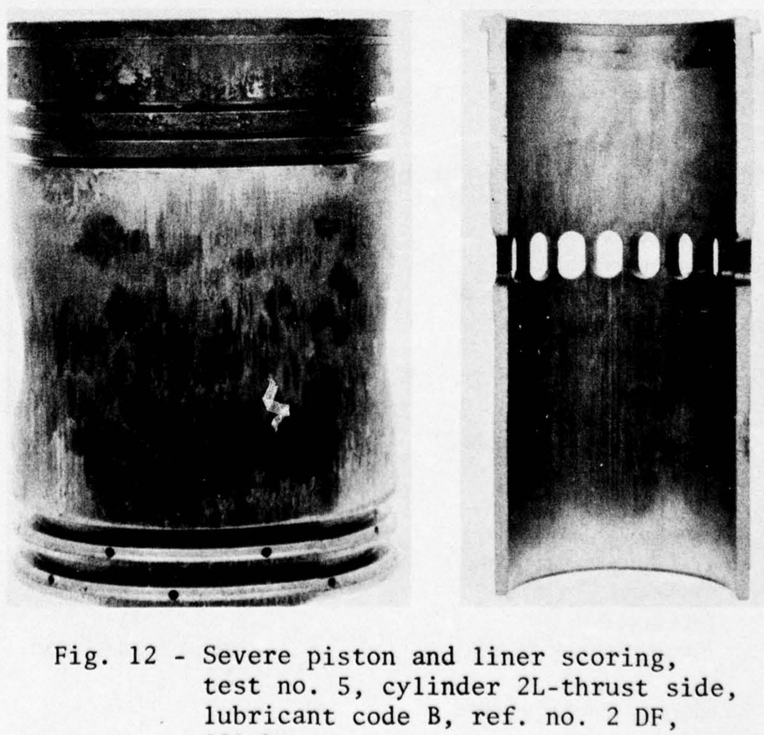


Fig. 12 - Severe piston and liner scoring, test no. 5, cylinder 2L-thrust side, lubricant code B, ref. no. 2 DF, 121 hours.

TABLE 7. LUBRICANT EFFECTS USING
HIGH SULFUR FUEL (HSF)

	Oil Code	
	A	C
Piston ring freedom		
No. hot stuck	0	3
No. cold stuck/pinched	0	2
Piston skirt demerits (avg)	4.0	3.6
Piston ring groove No. 2, avg % carbon fill	63	77
Piston weighted total demerit (WTD)	890	1048
Cylinder liner scuffing, % area		
Thrust side (avg)	13	13
Anti-thrust side (avg)	14	13
Piston ring gap change in thousandths of centimeters (thousandths of inches)		
Fire ring (avg)	33 (13)	18 (7)
Oil rings (avg)	33 (13)	25 (10)
Cylinder liner wear at top in ten thousandths of centimeters (ten thousandths of inches)		
Transverse (avg)	66 (26)	30 (12)
Longitudinal (avg)	18 (7)	13 (5)
Used oil final drain		
% Vis change at 37.8°C (100°F)	16.2	9.8
% Vis change at 99°C (210°F)	1.1	0.8
Sulfated ash, Δ	0.10	0.42
Carbon residue, Δ	0.66	0.86
Pentane insol (w/coag), Δ	0.29	0.29
Benzene insol (w/coag), Δ	0.24	0.20
Iron, ppm	183	136
Lead, ppm	29	20
Avg oil consumption, kg/hr (lb/hr)	0.24 (0.52)	0.24 (0.52)
Operating data (avg)		
Obs power, kW (BHp)	178.4 (287)	178.9 (288)
Fuel flow, kg/min (lb/min)	0.934 (2.06)	0.934 (2.06)
Jacket-out, °C (°F)	83 (181)	83 (181)
Oil sump, °C (°F)	113 (236)	113 (237)
Blowby flow, m^3/hr (cfh)	25.76 (910)	24.06 (850)
Endurance hours completed (210-hr target)	196	194

liner and oil ring wear. Liner and ring gap measurements tend to confirm the high wear rates in these areas using *either* lubricant. It appears that Code A lubricant out-performed the Code C lubricant in deposit control (i.e., ring freedom, piston ring groove, and skirt deposits), however the lack of wear protection using either of the two oils is an overriding factor. This shows that neither the low-ash (Code A) nor high-ash (Code C) oil could adequately lubricate this engine during continuous operation with this high-sulfur/high end-point diesel fuel.

NATO F-54 Type Fuel

In a like manner to that just described for the HSF, lubricant Codes A and C were used to determine acceptability of the mid-sulfur level NATO F-54 type fuel (Table 5, Test Nos. 11, 12 and 13). It is seen from the data in Table 8 that neither of these oils properly lubricated the engine during the use of the 0.64% sulfur F-54 fuel. Code A lubricant was involved in two separate instances of fire ring and exhaust valve breakage in Test No. 11 and the final wear data show significant piston ring wear and cylinder liner scuffing and wear throughout the engine. The first attempt in using Code C lubricant with this fuel resulted in catastrophic failures in the piston/cylinder liner area. There were five hot-stuck fire rings and severe piston/liner/scuffing/scoring in two cylinders as shown in Figures 13 and 14. The effects of this fuel/lubricant combination are believed to be real, but due to the short test duration (i.e., 28 hours) it was not believed meaningful to show the deposit, wear, and used oil data in Table 8. This test was repeated in another serial numbered engine (Test No. 13), and after completion of 112 endurance hours a steady decline in power was observed until the test was terminated at 131 hour with power output at 167.2 kw (269 BHp). Valve burning was the cause of the power loss, but the high used-oil iron content, ring sticking, piston deposits and cylinder liner wear indicate that this fuel and lubricant are incompatible with this engine. It is evident that neither of these lubricants could adequately protect this engine during continuous operation with this type F-54 diesel fuel.

Fuel Effects

Looking at fuel performance for a given lubricant is another way to examine the fuel/lubricant compatibility data. This approach is summarized in Table 9 for the low-ash Code A lubricant, and in Table 10 for the high-ash Code C lubricant. Photographs of selected pistons, liners, and rings are shown in Figures 15 through 18 for Code A lubricant, and in Figures 19 through 22 for Code C lubricant.

Low-Ash Code A Lubricant

Using the low-ash Code A lubricant to compare the effects of the HSF and F-54 fuel with the Reference No. 2 fuel in Table 9, it should be noted that two additional performance parameters have been added, i.e., inlet port plugging and piston ring face distress. It is evident from

TABLE 8. LUBRICANT EFFECTS USING NATO F-54 TYPE FUEL (0.64% SULFUR)

	Oil Code	
	A	C
Piston ring freedom		
No. hot stuck	0	0
No. cold stuck/pinched	2	3
Piston skirt demerits (avg)	3.8	2.8
Piston ring groove No. 2, avg % carbon fill	54	54
Piston weighted total demerit (WTD)	1038	1082
Cylinder liner scuffing, % area		
Thrust side (avg)	31	8
Anti-thrust side (avg)	23	5
Piston ring gap change in thousandths of centimeters (thousandths of inches)		
Fire ring (avg)	28 (11)	18 (7)
Oil rings (avg)	102 (40)	28 (11)
Cylinder liner wear at top in ten thousandths of centimeters (ten thousandths of inches)		
Transverse (avg)	81 (32)	56 (22)
Longitudinal (avg)	76 (30)	13 (5)
Used oil final drain		
% Vis change at 37.8°C (100°F)	8.4	10.8
% Vis change at 99°C (210°F)	0.6	0.8
Sulfated ash, Δ	0.27	0.27
Carbon residue, Δ	0.60	0.64
Pentane insol (w/coag), Δ	0.28	0.22
Benzene insol (w/coag), Δ	0.25	0.19
Iron, ppm	473	168
Lead, ppm	34	21
Average oil consumption, kg/hr (lb/hr)	0.22 (0.48)	0.26 (0.58)
Operating data (avg)		
Obs power, kW (BHp)	179.6 (289)	176.5 (284)
Fuel flow, kg/min (lb/min)	0.930 (2.05)	0.939 (2.07)
Jacket-out, °C (°F)	82 (179)	82 (179)
Oil sump, °C (°F)	116 (241)	112 (233)
Blowby flow, m^3/hr (cfh)	25.9 (915)	23.4 (825)
Endurance hours completed (210-hr target)	191	131[a]

[a]Data from Test No. 12 (28 hr) not shown.

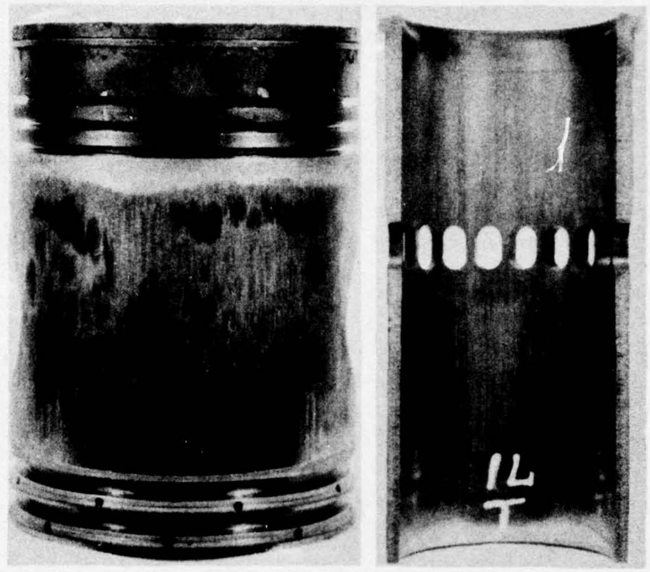


Fig. 13 - 1 Left thrust piston and liner - severe piston and liner scoring, test no. 12, oil code C, NATO F-54 DF, 28 hours.

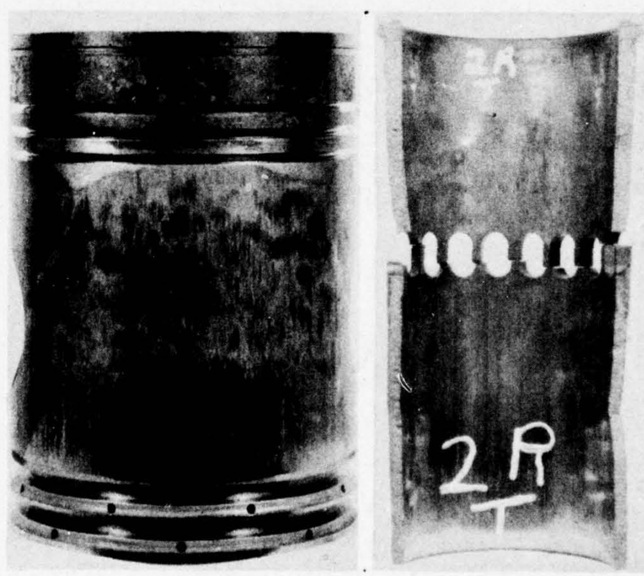


Fig. 14 - 2 Right thrust piston and liner - severe piston and liner scoring, test no. 12, oil code C, NATO F-54 DF, 28 hours.

TABLE 9. FUEL EFFECTS USING LOW-ASH LUBRICANT (CODE A)

	REF No. 2 DF	High Sulfur Fuel-HSF	NATO F-54 Type Fuel
Piston ring freedom			
No. hot stuck	0	0	0
No. cold stuck/pinched	0	0	2
Piston skirt demerits (avg)	3.9	4.0	3.8
Piston ring groove No. 2, avg % carbon fill	70	63	54
Piston weighted total demerit (WTD)	899	890	1038
Inlet port plugging (Relative)	Normal (Lowest)	Unacceptable (Highest)	Abnormal (High)
Cylinder liner scuffing, % area			
Thrust side (avg)	5	13	31
Anti-thrust side (avg)	2	14	23
Piston ring gap change in thousandths of centimeters (thousandths of inches)			
Fire ring (avg)	5 (2)	33 (13)	28 (11)
Oil rings (avg)	18 (7)	33 (13)	102 (40)
Piston ring face distress (avg)	Normal to light	Very severe	Most severe
Cylinder liner wear at top in ten thousandths of centimeters (ten thousandths of inches)			
Transverse (avg)	20 (8)	66 (26)	81 (32)
Longitudinal (avg)	10 (4)	18 (7)	76 (30)
Used oil final drain			
% Vis change at 37.8°C (100°F)	8.5	16.2	8.4
% Vis change at 99°C (210°F)	0.7	1.1	0.6
Sulfated ash, Δ	0.15	0.10	0.27
Carbon residue, Δ	0.47	0.66	0.60
Pentane insol (w/coag), Δ	0.31	0.29	0.28
Benzene insol (w/coag), Δ	0.33	0.24	0.25
Iron, ppm	54	183	473
Lead, ppm	10	29	34
Avg oil consumption, kg/hr (lb/hr)	0.30 (0.66)	0.24 (0.52)	0.22 (0.48)
Endurance hours completed (210-hr target)	210	196	191

TABLE 10. FUEL EFFECTS USING HIGH-ASH LUBRICANT (CODE C)

	REF No. 2 DF	High Sulfur Fuel-HSF	NATO F-54 Type Fuel
Piston ring freedom			
No. hot stuck	1	3	0
No. cold stuck/pinched	0	2	3
Piston skirt demerits (avg)	4.4	3.6	2.8
Piston ring groove No. 2, avg % carbon fill	72	77	54
Piston weighted total demerit (WTD)	1183	1048	1082
Inlet port plugging (Relative)	Normal (Lowest)	Abnormal (Highest)	Normal (Low)
Cylinder liner scuffing, % area			
Thrust side (avg)	15	13	8
Anti-thrust side (avg)	12	13	5
Piston ring gap change in thousandths of centimeters (thousandths of inches)			
Fire ring (avg)	13 (5)	18 (7)	18 (7)
Oil rings (avg)	38 (15)	25 (10)	28 (11)
Piston ring face distress (avg)	Normal to Severe	Very Severe	Most Severe
Cylinder liner wear at top in ten thousandths of centimeters (ten thousandths of inches)			
Transverse (avg)	64 (25)	30 (12)	56 (22)
Longitudinal (avg)	15 (6)	13 (5)	13 (5)
Used oil final drain			
% Vis change at 37.8°C (100°F)	20.4	9.8	10.8
% Vis change at 99°C (210°F)	1.5	0.8	0.8
Sulfated ash, Δ	0.52	0.42	0.27
Carbon residue, Δ	0.87	0.86	0.64
Pentane insol (w/coag), Δ	0.76	0.29	0.22
Benzene insol (w/coag), Δ	0.53	0.20	0.19
Iron, ppm	151	136	168
Lead, ppm	24	20	21
Avg oil consumption, kg/hr (lb/hr)	0.22 (0.49)	0.24 (0.52)	0.26 (0.58)
Endurance hours completed (210-hr target)	209.5	194	131[a]

[a]Data from Test No. 12 (28 hr) not shown.

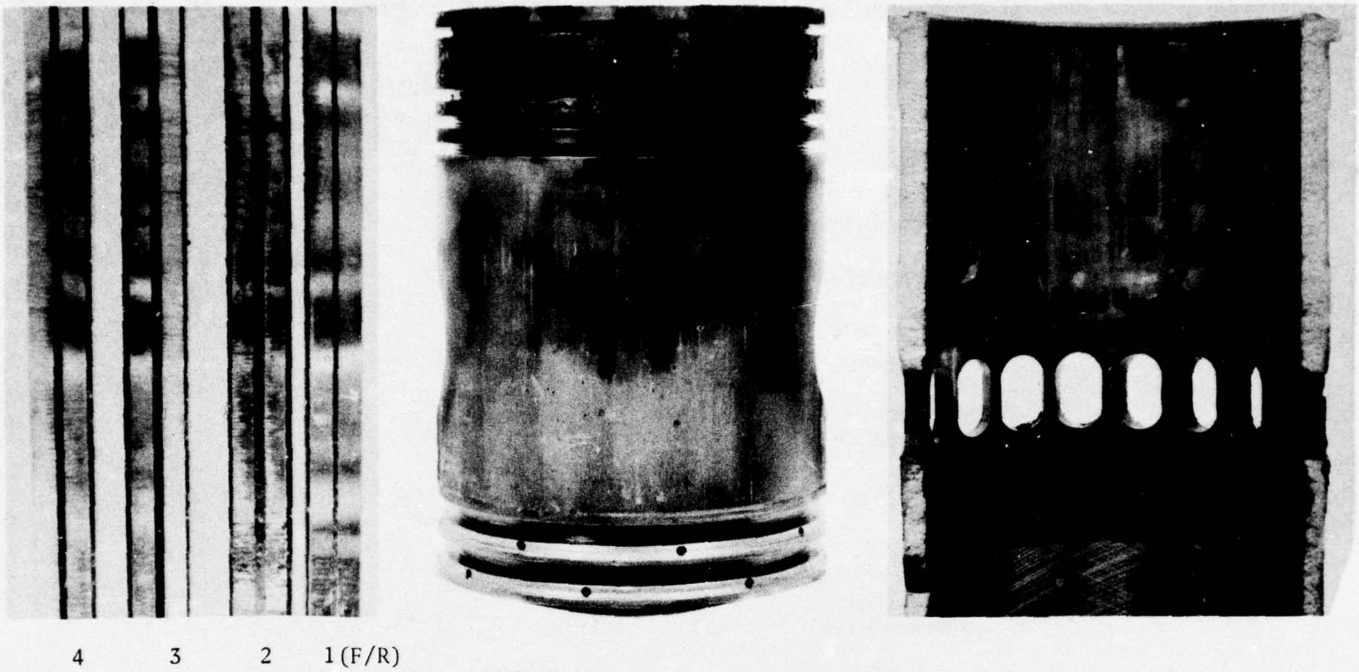


Fig. 15 - Condition of piston, rings and liner: test no. 7, 2L-anti-thrust, oil code A, High-Sulfur Fuel (HSF), 196 hours.

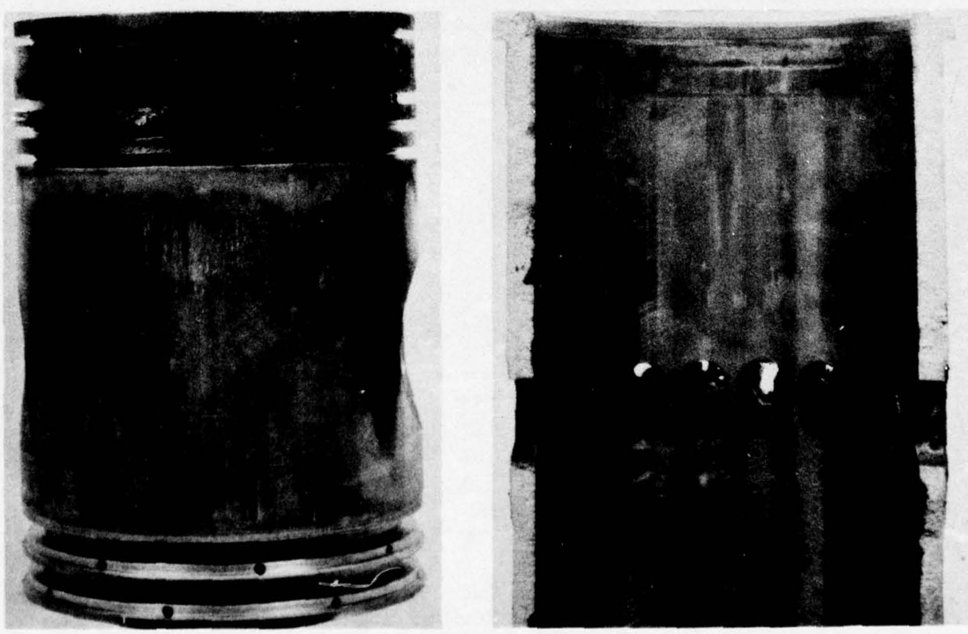


Fig. 16 - Condition of piston and liner: test no. 7, 3R-thrust, oil code A, High-Sulfur Fuel (HSF), 196 hours.

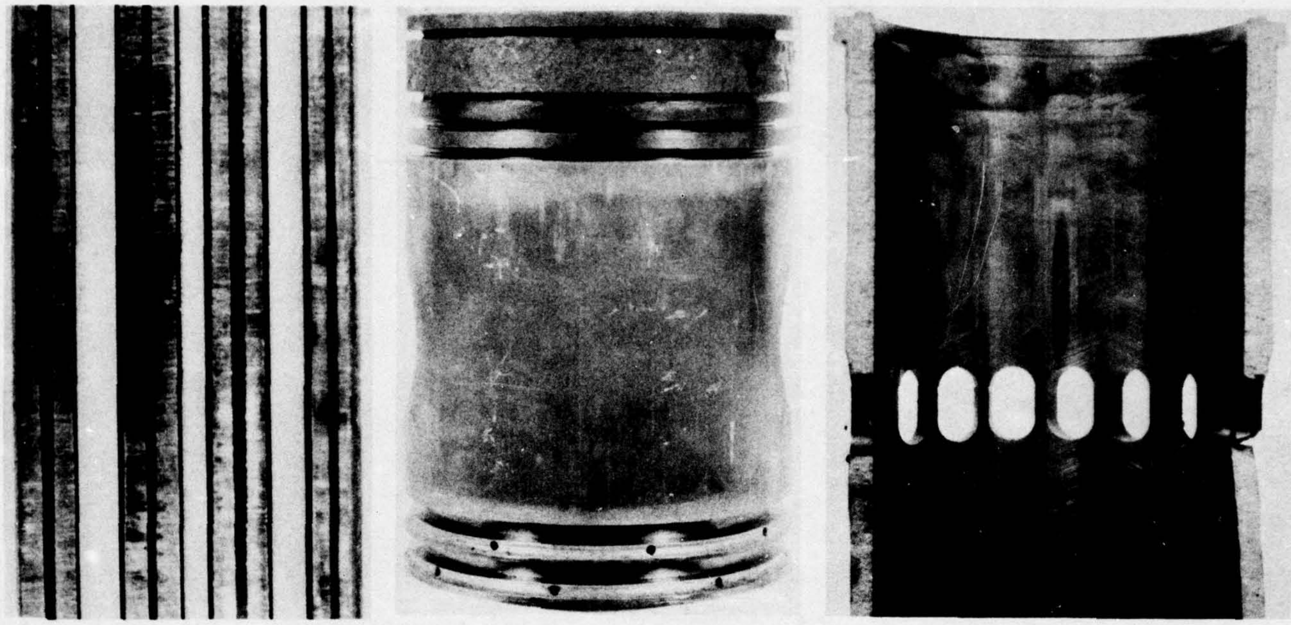


Fig. 17 - Condition of piston, rings and liner: test no. 11, 3R-thrust, oil code A, NATO F-54 DF, 191 hours.

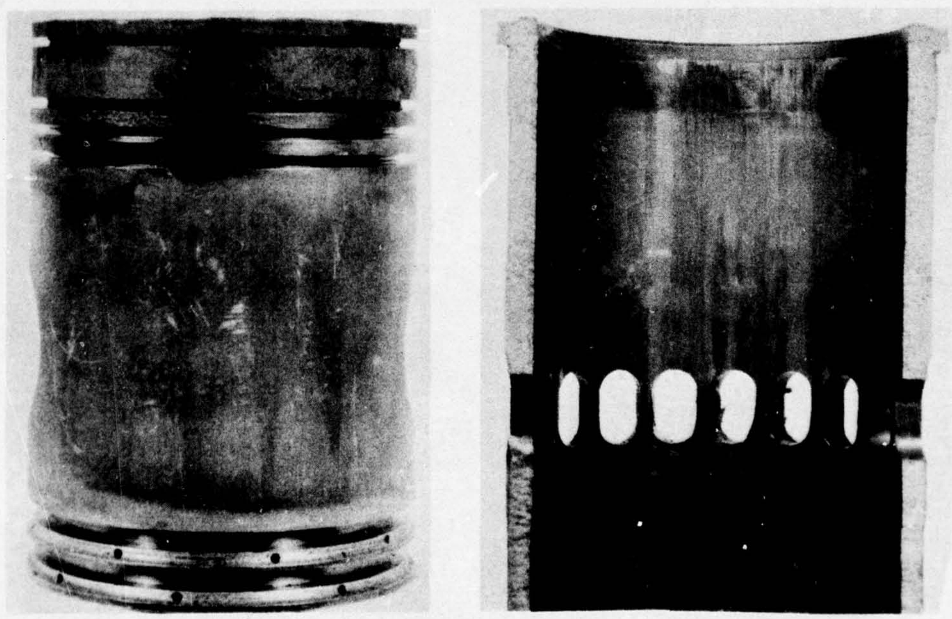


Fig. 18 - Condition of piston and liner: test no. 11, 3R-anti-thrust, oil code A, NATO F-54 DF, 191 hours.

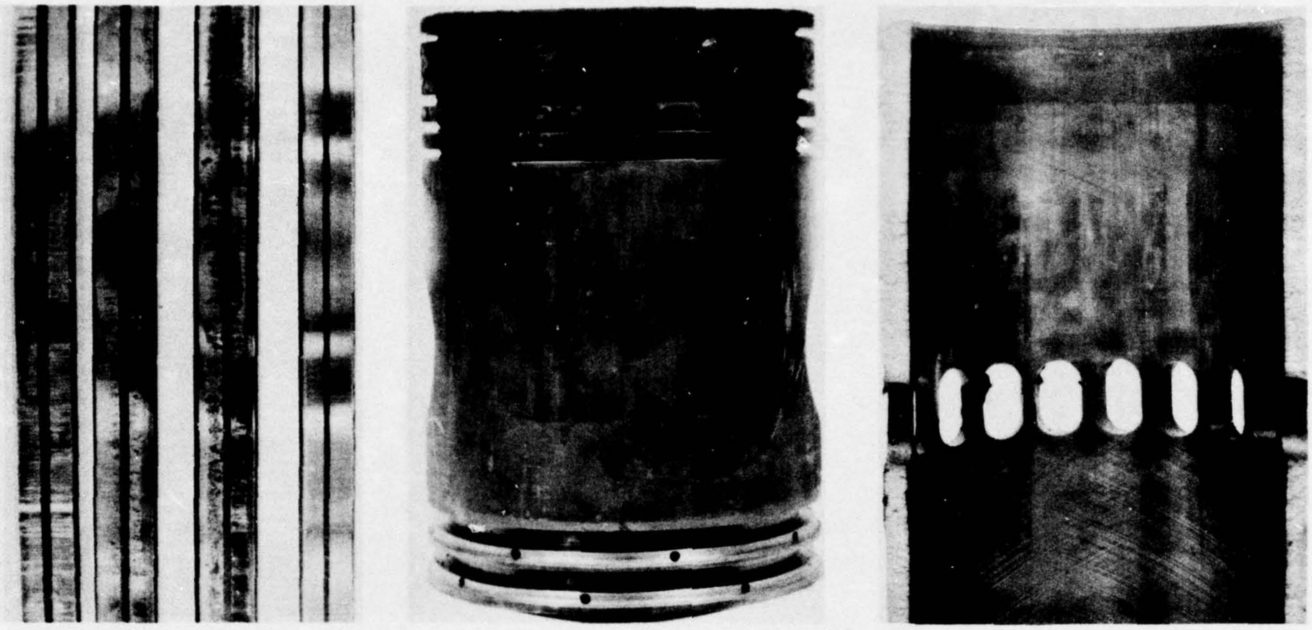


Fig. 19 - Condition of piston, rings and liner: test no. 6, 3R-anti-thrust, oil code C, High-Sulfur Fuel (HSF), 194 hours.

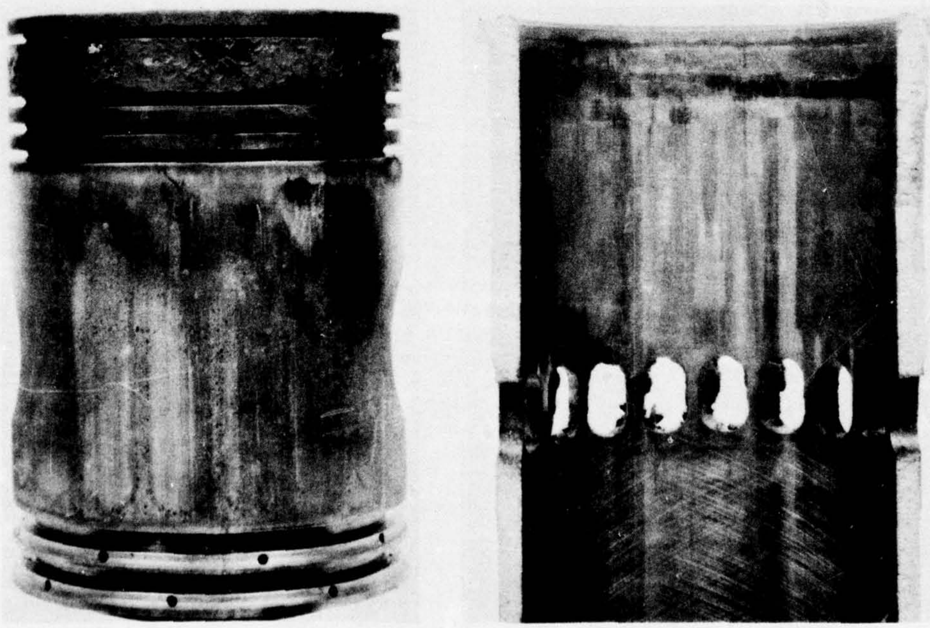
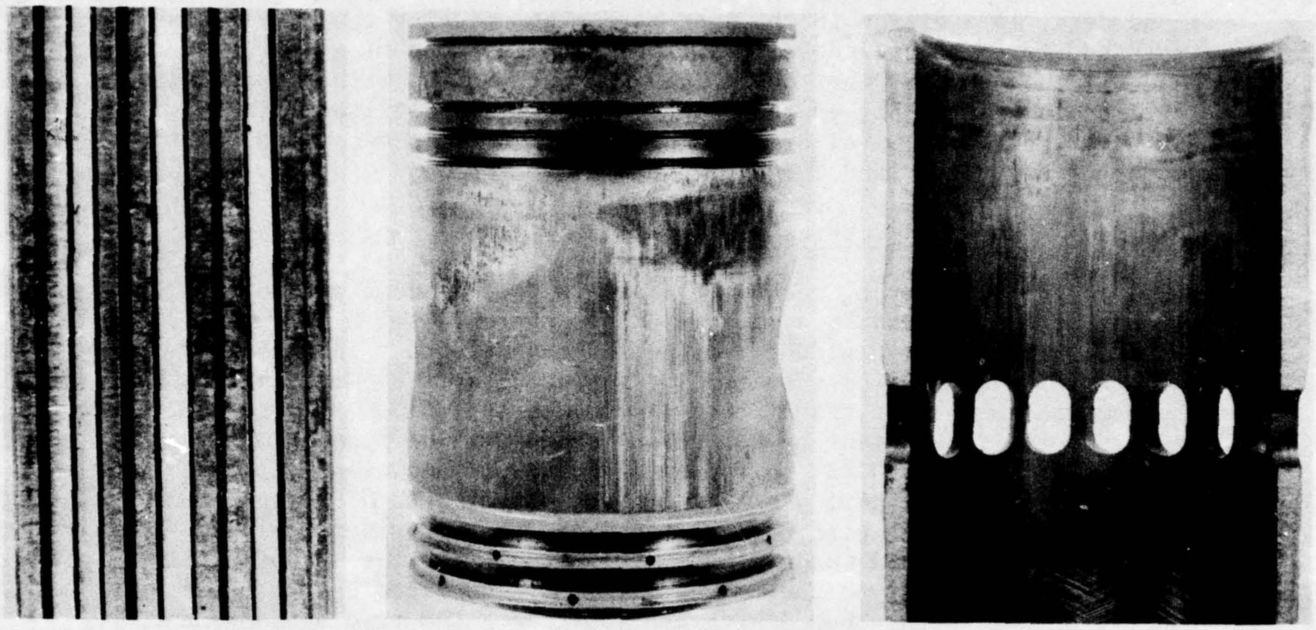


Fig. 20 - Condition of piston and liner: test no. 6, 3R-thrust, oil code C, High-Sulfur Fuel (HSF), 194 hours.



4 3 2 1(F/R)

Fig. 21 - Condition of piston, rings and liner: test no. 13, 2L-thrust, oil code C, NATO F-54 DF, 131 hours.

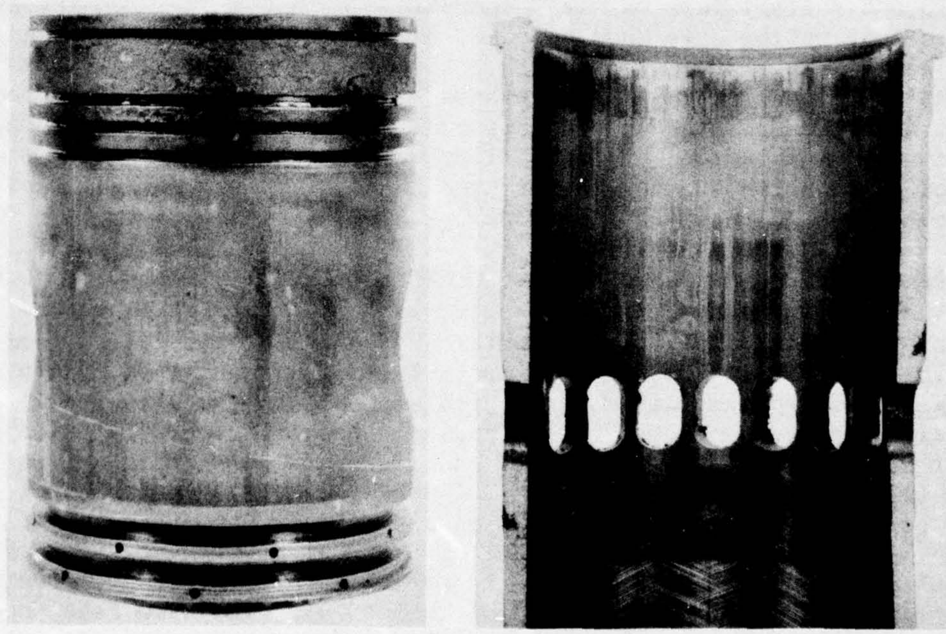


Fig. 22 - Condition of piston and liner: test no. 13, 2L-anti-thrust, oil code C, NATO F-54 DF, 131 hours.

these data, in addition to the increased ring sticking tendencies, the increased level of cylinder liner scuffing, liner and ring wear, and used-oil iron content that the engine *is incompatible* with higher sulfur level fuels and the higher end-point temperature associated with the HSF. The increased level of liner port plugging is shown in the photographs of Figures 15 and 16.

High-Ash Code C Lubricant

Similarly when the Code C lubricant is used to compare the fuel effects of the HSF and F-54 fuel with the Reference No. 2 fuel in Table 10, it is immediately evident that lubrication distress increases from the otherwise *borderline* situation using the reference fuel. For example, the *measured wear* in terms of ring gap increase, cylinder liner wear, and used oil iron content do not show the HSF or F-54 type fuel to be more severe than the 0.42% sulfur reference fuel. However, increased ring sticking, inlet port plugging tendencies with the HSF (Figures 19 and 20) and increased piston ring face distress are evidence of higher operating severity and *unacceptable performance* with the use of either the HSF or the F-54 type fuel. One might have expected better performance from this highly based/high ash lubricant, the type of lubricant that normally would be selected for use during operation with higher sulfur level fuels.

Supplemental Test Fuel Analyses

The data presented in Tables 5 through 10 indicated that the NATO F-54 (0.64% sulfur) fuel was less compatible with the 6V53T engine and the two lubricating oils Code A and C, than the high sulfur/high end-point fuel [1.2% S/396°C (744°F) EP]. Since this was somewhat unexpected, additional analyses of the NATO F-54 test fuel were conducted to determine if characteristics of this fuel other than sulfur level may have contributed to the incompatibility. To further enhance this study, samples of the blending components used to manufacture the F-54 fuel were obtained and analyzed individually.

The reference No. 2 diesel fuel and the NATO F-54 fuel were obtained from the same refinery and it was determined that the two contained common blending stocks with the addition of a third material to formulate the F-54 fuel. The high sulfur fuel (HSF) was obtained from a different refinery and was manufactured with blending stocks from entirely different sources. The blending composition, distillation and sulfur properties of the components and finished fuels are shown in Table 11. The fuel described as MIL-L-9000G, 1-G/3-71 is in effect a fuel used for qualification of oils under Military Specification MIL-L-9000G[26], using Methods 339 and 341 of FTMS 791B, which specify a 1% *natural sulfur* fuel. MIL-L-9000 oils are used to service Navy diesels operated on MIL-F-16884 marine diesel fuel (DFM). The NATO F-54 fuel was prepared by diluting the 1-G (1% sulfur) fuel with stream diesel to reduce the sulfur level. Table 12 shows the various analyses conducted on the components and finished fuels F-54 and reference No. 2 diesel. The HSF was no longer available for analysis.

TABLE 11. COMPARISON OF DIESEL ENGINE-LUBRICANT TEST FUELS

Blend Component	Volume Percent			Diesel Engine Test Fuels: MIL-L-9000G 1-G&3-71[a]	Ref. No. 2 DF 1-H/1-G MIL-L-2104C[b]	NATO F-54	High Sulfur Fuel–HSF
No. 3 cycle oil	100	–	–	26	0	17	N/A
No. 2 furnace oil	–	100	–	54	50	36	N/A
Heavy or steam diesel	–	–	100	20	50	47	N/A
Total fuel, % vol	–	–	–	100	100	100	100
Property	**Typicals**			**Actual**			
Distillation, temp, °C (°F)							
IBP	227 (440)	226 (438)	226 (438)	209 (408)	210 (410)	227 (440)	204 (399)
10%	236 (456)	243 (470)	241 (465)	238 (460)	242 (468)	248 (478)	231 (447)
90%	256 (492)	308 (586)	332 (630)	306 (583)	317 (603)	323 (613)	359 (679)
EP	279 (534)	323 (613)	369 (697)	343 (650)	365 (689)	363 (685)	396 (744)
Natural sulfur, % wt	1.4	0.89	0.06	1.00	0.42	0.64	1.20

[a]Para 4.6.2 of MIL-L-9000G, Methods 341.4 and 339.5 of FTMS 791B, respectively.
[b]Para 4.1, Fuel, of Method 346.2 and 341.4 of FTMS 791B, respectively.

N/A–Not applicable, HSF was manufactured with blending stocks from a different source.

Examination of the data for the F-54 fuel and comparison with the data for the reference No. 2 diesel and HSF does not indicate any glaring characteristic that can be pinpointed as the chief cause of the poor performance in the 6V53T engine test. However, a number of properties are below par and one of the components, the #3 cycle oil, has very undesirable properties. More specifically, the high steam jet gum, 20.9 mg/100 ml, of the F-54 compared to 5.7 for the reference fuel, and the high accelerated stability value, 7.4 mg/100 ml vs. 2.1 mg/100 ml for the reference fuel and 1.5 mg/100 ml for the HSF indicate an unstable fuel which probably contributed or initiated the deposit manifestations occurring in the engine proper. The relatively high level of olefins, oxygenated compounds, napthenic acid and pyrrole nitrogen content of the #3 cycle oil probably were the main contributors to the instability of this fuel. It can be hypothesized that as deposits were formed due to the instability of the fuel, the napthenic/peroxy acids probably concentrated in the deposit formations. This "enrichment" of corrosivity when coupled with the sulfur combustion products probably induced the premature failure of the engine during the compatibility tests.

Endurance Test Cycle Effects

Lubricant Codes A and C were used to examine test-cycle severity effects and to further study the compatibility of these two MIL-L-2104C products with the 6V53T engine. The results are summarized in Table 13 where it is seen that during tracked-cycle operation with the low-ash Code A lubricant the engine experienced significant increases in upper ring belt deposits and ring and liner wear. The two-fold increase in used-oil wear metals is further evidence of the increased wear level. Test cycle severity effects are not as obvious when the data for the high-ash Code C lubricant are studied. It is seen that there are no differences in ring belt deposits and little if any differences in used oil degradation. However, the three cold stuck rings and the slightly higher level

TABLE 12. SUPPLEMENTAL ANALYSES ON 6V53T COMPATIBILITY TEST FUELS[(a)] AND THEIR COMPONENTS

Analysis	Heavy Diesel AL-5647-F	No. 2 Furnace Oil AL-5648-F	No. 3 Cycle Oil AL-5649-F	NATO F-54 Fuel AL-5544-F	Ref. No. 2 DF AL-5455-F
Elemental analyses, % wt					
Carbon	87.19	86.48	87.50	87.00	86.72
Hydrogen	12.78	13.36	10.58	12.47	12.78
Nitrogen	0.02	0.01	0.02	0.01	0.11
Oxygen	None	None	1.89	0.48	0.32
Sulfur	0.04	0.72	1.88	0.64	0.42
Trace metals, ppm					
Sodium	ND	ND	0	0.02	0.02
Potassium	ND	ND	0	0	0
Vanadium	ND	ND	0	0	0
Iron	ND	ND	0.42	0.38	0.39
Copper	ND	ND	0	0.10	1.07
Silicon	ND	ND	ND	ND	ND
Ash, % wt	0	0	0	0.0010	0.0015
Basic nitrogen, % wt	0.0023	0.001	0.002	0.0025	ND
Pyrrole nitrogen, ppm	1.12	0.30	34.51	3.22	ND
Napthenic acid, ppm	ND	ND	142	52	ND
Free sulfur, ppm	0.80	8.3	2.5	3.5	ND
Hydrocarbon type analysis					
FIA, % vol					
Aromatics	31	31	62	39	ND
Olefins	2	2	6	3	ND
Saturates	67	67	32	58	ND
HPLC, % wt					
Aromatics	22.7	27.7	64.2	29.6	25
Saturates and olefins	77.3	72.3	35.8	70.4	75
UV % wt–estimate					
Mono-aromatics	20.5[b]	23.5[b]	ND	33	ND
Di-aromatics	6.1[b]	3.6[b]	ND	9	ND
Tri-aromatics	0.9[b]	0.4[b]	ND	0.9	ND
Aniline point, °C (°F)	66.7 (152)[b]	64.4 (148)[b]	ND	61.1 (142)	62.8 (145)
Conjugated dienes, % wt	ND	ND	ND	0.08	0.14
Steam jet gum, mg/100 ml	ND	ND	ND	20.9	5.7

[a]The high sulfur fuel (HSF) was no longer available for analysis.
[b]Value determined on earlier samples of these materials. ND–Not determined.

TABLE 13. TEST CYCLE SEVERITY EFFECTS
(REF. NO. 2 FUEL–0.42% SULFUR)

Oil Code/Ash =	Code A–Low Ash		Code C–High Ash	
Test Cycle =	210-hr Wheeled	240-hr Tracked	210-hr Wheeled	240-hr Tracked
Piston ring freedom				
No. hot stuck	0	0	1	0
No. cold stuck/pinched	0	0	0	3
Piston skirt demerits (avg)	3.9	3.5	4.4	3.0
Piston ring groove No. 2, avg % carbon fill	70	80	72	74
Piston weighted total demerit (WTD)	899	1177	1183	1136
Cylinder liner scuffing, % area				
Thrust side (avg)	5	4	15	11
Anti-thrust side (avg)	2	3	12	5
Piston ring gap change in thousandths of centimeters (thousandths of inches)				
Fire ring (avg)	5 (2)	20 (8)	13 (5)	23 (9)
Oil rings (avg)	18 (7)	28 (11)	38 (15)	38 (15)
Cylinder liner wear at top in ten thousandths of centimeters (ten thousandths of inches)				
Transverse (avg)	20 (8)	61 (24)	64 (25)	81 (32)
Longitudinal (avg)	10 (4)	20 (8)	15 (6)	25 (10)
Used oil final drain				
% Vis change at 37.8°C (100°F)	8.5	10	20.4	21
% Vis change at 99°C (210°F)	0.7	0.7	1.5	1.6
Sulfated ash, Δ	0.15	0.16	0.52	0.39
Carbon residue, Δ	0.47	0.62	0.87	0.83
Pentane insol (w/coag), Δ	0.31	0.40	0.76	0.50
Benzene insol (w/coag), Δ	0.33	0.36	0.53	0.46
Iron, ppm	54	116	151	116
Lead, ppm	10	20	24	21
Avg oil consumption, kg/hr (lb/hr)	0.30 (0.66)	0.19 (0.42)	0.22 (0.49)	0.23 (0.51)
Endurance hours completed	210	240	209.5	240

of ring and liner wear suggests an increase in severity level. The fact that neither lubricant experienced significant changes in physical properties is attributed to the oil change that is made midway in the tracked-cycle test (i.e., at 120 hrs). These results show that (1) both lubricants are compatible with the 6V53T engine, and (2) the tracked-vehicle test cycle is judged to be more severe than the wheeled-vehicle test cycle for this engine. Based on the earlier discussion of the high-ash lubricant in the wheeled-test cycle (where performance was judged borderline acceptable), it is still evident from the data in Table 13, that this high-ash lubricant should be considered *borderline acceptable* for continuous use in the 6V53T engine. Finally, the results in Table 13 suggest that a significant increase in test severity might be achieved if the 120-hr oil change were to be eliminated in the tracked-cycle test procedure; and similarly a significant severity increase would be expected in the tracked-cycle test procedure if a higher sulfur-level test fuel were used.

CONCLUSIONS AND RECOMMENDATIONS

The U.S. Army in order to maintain a high degree of *readiness* must have an adequate supply of fuels and lubricants of *known* performance capabilities--not only for CONUS procurement and use, but also for OCONUS procurement and usage. With the diverse mix of diesel powered equipment found in today's combat/tactical fleet this would seem to create problems of insurmountable proportion. Indeed it does, compounded by the dilemma of high-ash oils and high-sulfur fuels for use in the Army two-cycle diesel engine segment of the combat/tactical fleet. But this problem is *not* without solution, as it is hoped that the current work reported herein, is a step in the direction of providing additional insight into this ash-level/sulfur-level problem. Experience gained during the 1940's in both two and four-cycle diesel engines[27-31], was perhaps less dramatic, but nevertheless, consistent with that observed in this modern high-output two-cycle military diesel engine.

Recent experience[32] of the U.S. Navy showed that Navy two-cycle (and four-cycle) diesel engines achieve *unacceptable wear levels* in 1000-hour endurance tests using fuels having 1.00% and higher natural sulfur. While this is considered unacceptable to the Navy, the fact that the Army's 6V53T failed to achieve a targeted 210 hours in five attempts using fuels of 1.2% and 0.64% sulfur levels seems inconsistent. It is believed that the Army's simulated stop-and-go 210-hour wheeled-vehicle and 240-hour tracked-vehicle test cycles significantly reduce engine life in two-cycle diesels when fuels having greater than 0.50% natural sulfur are used. Such stop-and-go, hot and cold operating test cycles designed to correlate with Army vehicle/proving ground operation are presumably more severe than the Navy's endurance tests designed to correlate with shipboard propulsion or generator service. However, this is not known for certain, since there is the possibility that the Navy's MIL-L-9000 diesel engine lubricants could control the detrimental effects of *high-sulfur fuel* better than the MIL-L-2104C engine oils.

Based on the results of the current study and the Army's experience with two-cycle diesels, it is *concluded*:

1. Tests produced wide differences in results with oils of differing additive chemistry demonstrating ability of the 6V53T engine and the test procedures to discriminate lubricant performance.

2. The low-ash level lubricant (Code A) and mid-ash level *fielded lubricant* (Code D) were determined to be compatible with the *lubricant-sensitive* 6V53T diesel engine. It is expected then, that lubricants of *these types* would be compatible with the Army's entire two-cycle diesel engine fleet.

3. The 6V53T *may not be compatible* with *all* MIL-L-2104C lubricants. Certain *other high-ash lubricants* might produce *better* two-cycle diesel engine performance, but *others* might produce a *worse* performance than the already borderline performance experienced with the high-ash Code C lubricant.

4. The low-ash level Code B lubricant is judged incompatible with the 6V53T engine due to its proneness to severe piston and liner scuffing. The cause of the severe scuffing was not determined, but its evidence was confirmed in two tests using the same serial-numbered engine in which Code C lubricant was successfully evaluated.

5. If it is considered that the lubricants used to evaluate the special fuel blends are typical MIL-L-2104C products, then the *high sulfur/high end-point fuel (HSF) is incompatible* for *continuous* use in Army two-cycle diesel engines. This is based on observations of increased engine deterioration resulting in reduced performance, leading to increased maintenance and reduction in engine life.

6. Similarly, the particular diesel fuel blended to meet NATO F-54 limits is *considered incompatible* with the Army's ground-vehicle two-cycle diesel engine family. Continuous use of a fuel of this type would produce engine deterioration resulting in reduced performance and possible increased maintenance, and reduction in engine life within the Army's *two-cycle diesel engine family*.

7. The observed *catastrophic distress*, i.e., piston/ring/exhaust valve failures and relatively high deposit and wear levels, was probably caused by the characteristics of this particular NATO F-54 fuel blend, but *not necessarily by sulfur content only*.

8. The tracked-vehicle test cycle is judged to be more severe than the wheeled-vehicle test cycle for operation of the 6V53T engine. Wear and piston deposits with the low ash Code A lubricant and fire ring pinching and wear with the high ash Code C lubricant indicated this severity.

Concerning recommendations, the Army has recognized for many years, the need for a *year-around/multiviscosity grade lubricant* for the combat/tactical fleet. Like many of the U.S. diesel engine manufacturers, the

Army has always believed (based on experience), that lubricant formulation technology and test-evaluation methodology were inadequate to successfully develop a multi-viscosity grade diesel engine lubricant. But now, with the Army's relatively recent experiences[18,19] with synthetic arctic engine oils and increased confidence in the discriminating abilities of the 210-hr/240-hr endurance cycles reported herein, a critical look at SAE 10W30/10W40 candidates should be undertaken for potential use in the Army diesel fleet.

Since latest information shows that U.S. Army diesel powered equipment must frequently operate with fuels having sulfur levels from 0.60 to 1.00 percent, consideration should be given to the regular use of test fuel having 1.00 percent natural sulfur for *military* qualification purposes. In relation to the current work, the following specific *recommendations* are made:

1. The Army currently plans to retrofit its series 71 fielded two-cycle diesel engines at overhaul, replacing the more *lubricant sensitive* trunk pistons with the new, less severe[33,34] cross-head pistons. This should take several years to complete, and there are no plans to retrofit the series 53 two-cycle diesel pistons, continuing to equip these engines with the older style trunk-type pistons. Since the more lubricant sensitive trunk style piston will be in the Army's two-cycle diesels for a long time, this type engine configuration should be retained for evaluating Army engine oils.

2. The tracked-vehicle test cycle should be adjusted as required making use of an *Army trunk-piston* equipped *two-cycle diesel engine* to evaluate multi-viscosity grade candidate lubricants for MIL-L-2104C; both *conventionally formulated* (polymer thickened mineral oils) and *synthetic-based* lubricants should be considered; however, since the *Army's experience* shows that the volatility characteristics of SAE 10W oils cause catastrophic piston/liner failures in *high-output two-cycle diesel engines*, it is unlikely that a multigrade 10W30/40 lubricant utilizing a *conventional* mineral oil base stock having the same volatility characteristics as the SAE 10W oil could provide acceptable performance in this class of engines.

3. More research should be conducted into the effects of diesel fuel composition on engine durability and performance. The Army has intensified its own research in this area in an attempt to better understand the *fuel compositional effects* reported herein.

4. If some success can evolve from the above Army research efforts, in that engine prodegradent components can be identified in the fuel, consideration should be given to neutralizing or inhibiting these "bad actors" either by (1) the development and use of fuel additives, (2) by exploring other avenues of lubricant formulation technology (MIL-L-21260 preservative oils and MIL-L-9000 shipboard diesel engine oils are two examples), and (3) modification to fuel refining processes.

5. Properly formulated synthetic engine oils should be considered as potential problem solvers of the catastrophic distress observed in this work when undesirable fuel characteristics are better identified; this would apply to diesel fuels of mid-range sulfur content (i.e., 0.35 - 0.50%), and high-sulfur content (i.e., up to 1.00%).

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APPENDIX I
Summary of Engine Endurance Test Procedures

1. Clean, measure, and rebuild test engine using new cylinder liners, pistons, piston rings, connecting rod and main bearing inserts, in accordance with standardized buildup procedures specified by appropriate Army Technical Manuals or engine manufacturer bulletins[1,3]. Due to the unavailability of new or rebuilt 6V53T engines outside the military supply system, it was necessary to rebuild test engines already on hand at AFLRL prior to each test. This was further necessitated by the fact that military depot overhauled engines were not readily available.

2. Run-in the engine and perform full-load performance calibration.

3. Conduct compatibility endurance test: either 210-hr wheeled-vehicle cycle or 240-hr tracked-vehicle cycle.

4. Perform post-test full-load performance calibration.

5. Disassemble, inspect, and rate engine in accordance with CRC diesel engine rating practices, remeasure engine to determine wear of critical components, conduct used oil analyses, and photograph typical pistons, liners, rings, and any unusual parts condition.

Compatibility Endurance Test*

The compatibility endurance test consists of repeating the endurance cycle for * *days without interruption for * hours of engine operation.* During test, the engine is to be operated using arctic anti-freeze as the coolant. Coolant temperatures must be maintained within ±1°C (±2°F) of the listed value; and, *the idle temperature must be obtained within ten minutes after starting each idle portion of the cycle.* Coolant will be used to control the *oil temperature* which *shall not exceed* 121°C (250°F). The fuel is to be controlled at 32°±3°C (90°±5°F) temperature by use of an external water to fuel heat exchanger.

Notes:

1. Maximum allowable oil sump temperature = 121°C (250°F).

2. No oil drains during wheeled-vehicle test cycle; 120 hour oil drain during tracked-vehicle cycle, with filter change.

3. Oil Samples:

   Wheeled-Vehicle Cycle

   a. A .24 liter (one-half pint) sample every 14 hours--12 total.

   b. A .4731 liter (one pint) sample every 70 hours--3 total.

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* - Wheeled Vehicle Cycle = 15 days for 210 hours operation.
* - Tracked Vehicle Cycle = 12 days for 240 hours operation.

APPENDIX I (cont.)

Tracked-Vehicle Cycle

a. A .24 liter (one-half pint) sample every 20 hours--10 total.

b. A .95 liter (one quart) sample at 120 and 240 hours--2 total.

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Wheeled-Vehicle - Endurance Cycle

Period	Time, hrs.	Load, %	Speed, rpm	Coolant Temp, °C(°F)
1	2	100	2800±20--Full Power	82±1(180±2)
2	1	0	650±25--Idle	38±1(100±2)
3	2	100	2800	82(180)
4	1	0	650	38(100)
5	2	100	2800	82(180)
6	1	0	650	38(100)
7	2	100	2800	82(180)
8	1	0	650	38(100)
9	2	100	2800	82(100)
10	10	----------Shutdown----------		

Tracked-Vehicle - Endurance Cycle

Period	Time, hrs.	Load, %	Speed, rpm	Jacket-Out Temp, °C(°F)
1	0.5	0	650±25--Idle	38(100)
	2	100	2800±20--Full Power	82(180)
	0.5	0	650±25--Idle	38(100)
	2	100	2200±20--Peak Torque	82(180)
2	0.5	0	650	38(100)
	2	100	2800	82(180)
	0.5	0	650	38(100)
	2	100	2200	82(180)
3	0.5	0	650	38(100)
	2	100	2800	82(180)
	0.5	0	650	38(100)
	2	100	2200	82(180)
4	0.5	0	650	38(100)
	2	100	2800	82(180)
	0.5	0	650	38(100)
	2	100	2200	82(100)
5	4	----------Shutdown----------		